Superconducting Nanowire Single Photon Detectors For Deep Space Optical Communication

Matt Shaw

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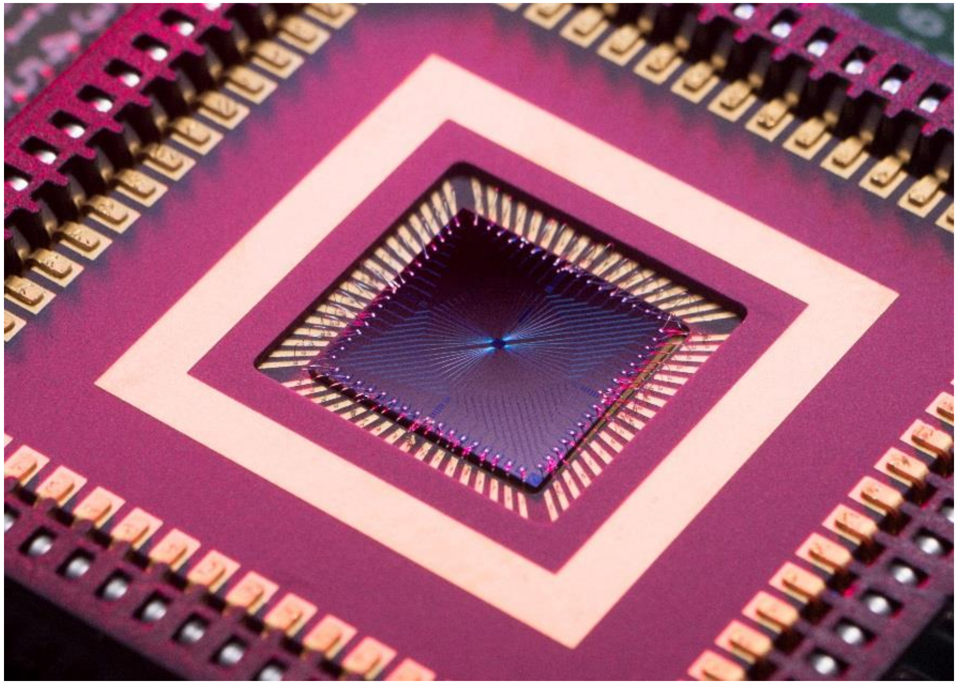

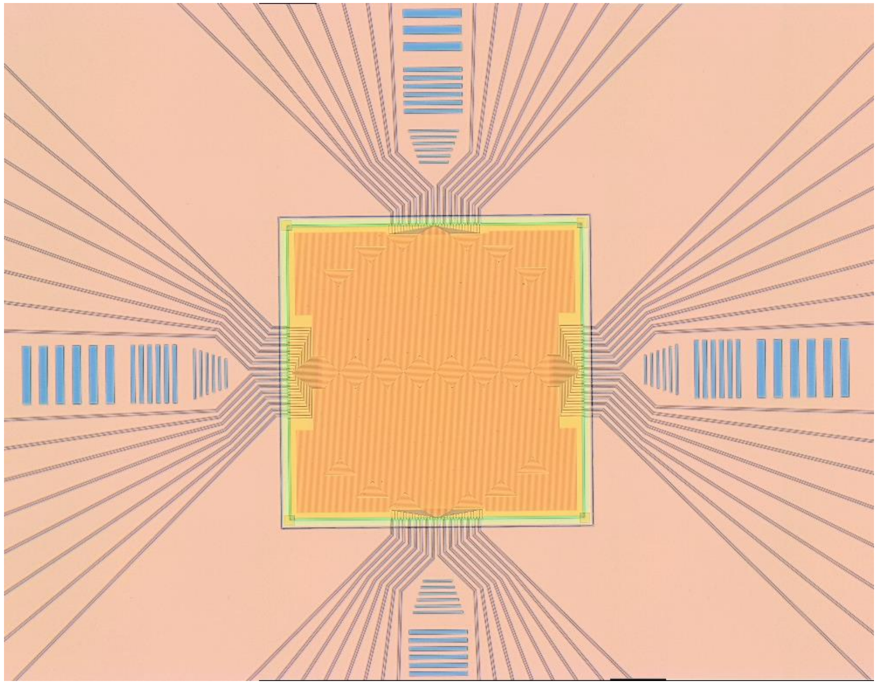

JPL SNSPD Development Team

Jet Propulsion Laboratory
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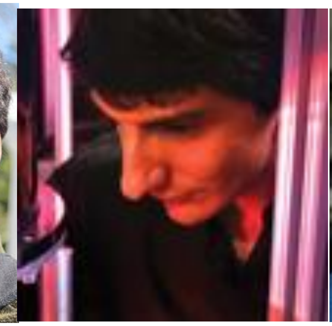
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Research Interests

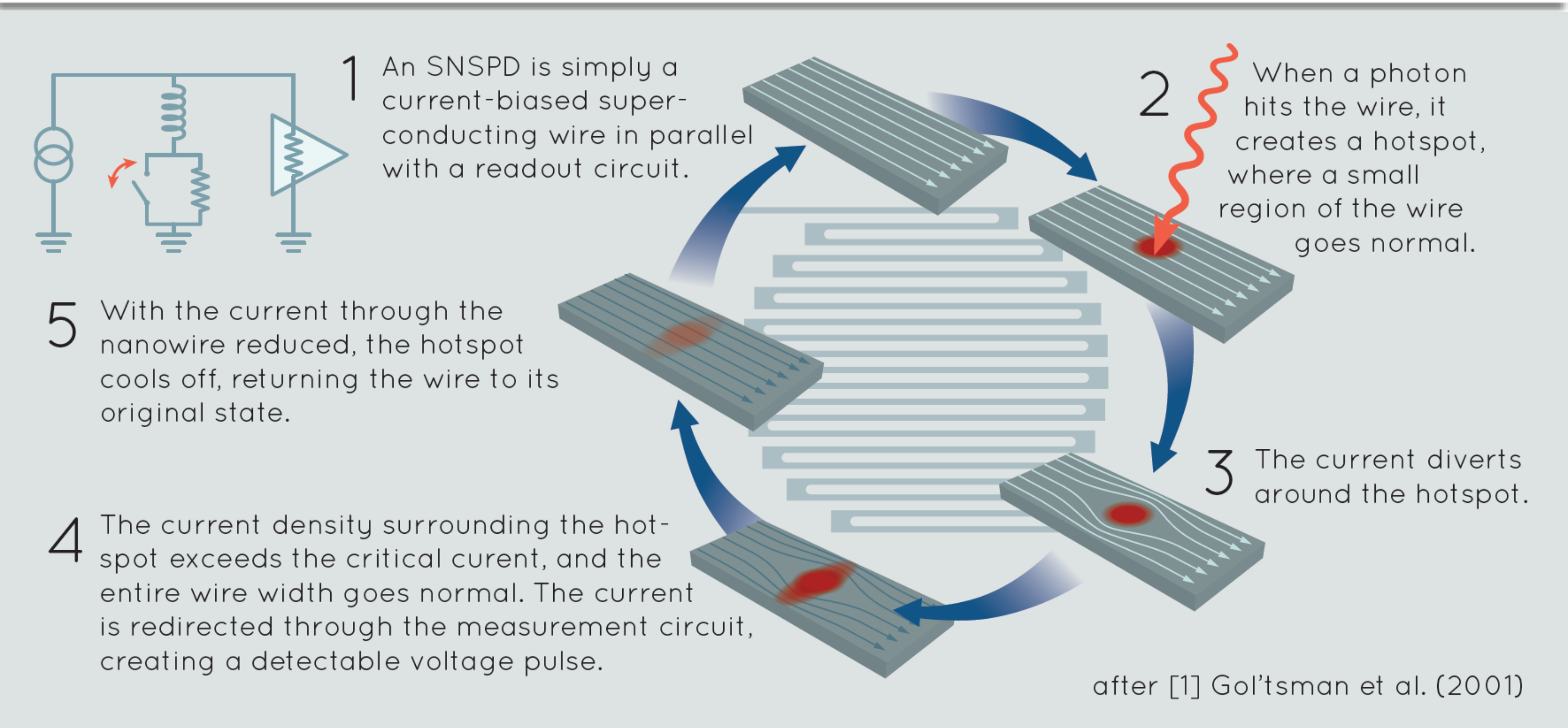
Superconducting Nanowire Single Photon Detectors

- *Engineering superior efficiency, time resolution, dark counts, active area, wavelength response, pixel count*
- *Understanding fundamental device physics and fundamental limitations*
- *Prototyping new device concepts*
- *Integration into experiments to enable new science*

Optical Communication from Deep Space

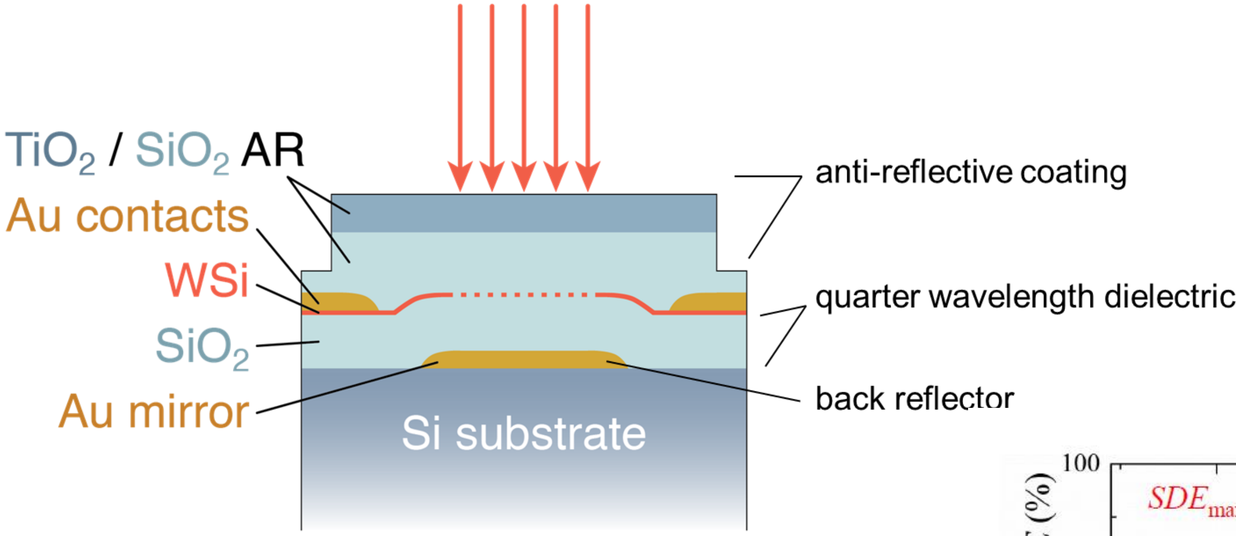
- *Demonstration of high rate optical communication from 0.6 – 2.7 AU*
- *Development of ground receiver technology for deep space optical communication*
- *Demonstration of high rate optical communication from lunar range (0.01 AU)*
- *Demonstration of novel high photon information efficiency communication links in the laboratory*

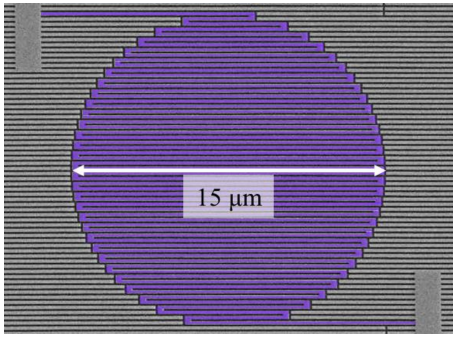
SNSPD Device Concept

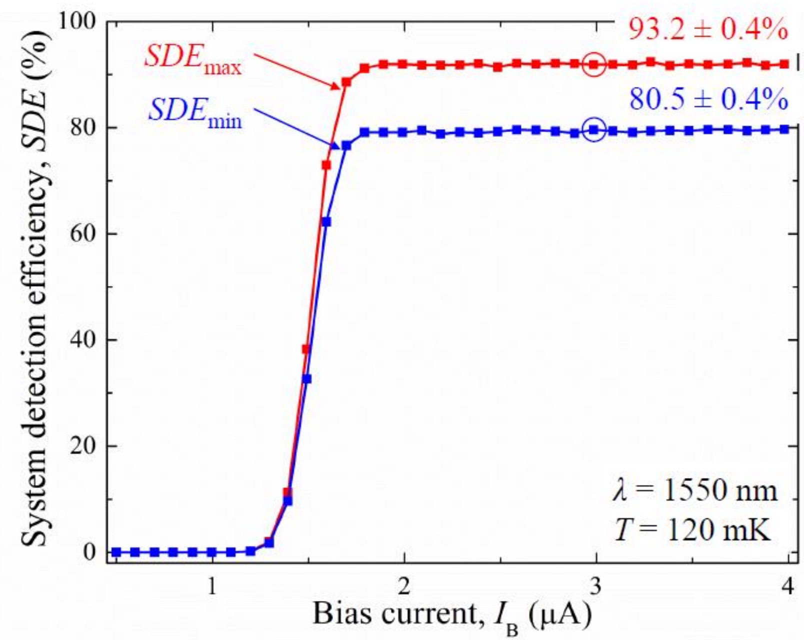


- Highest performing detector available for time-correlated single photon counting, UV to mid-IR
- Requires 1 – 4 Kelvin cryogenic cooling
- Commercial single-pixel SNSPDs have been widely adopted by the quantum optics community

WSi SNSPD Architecture





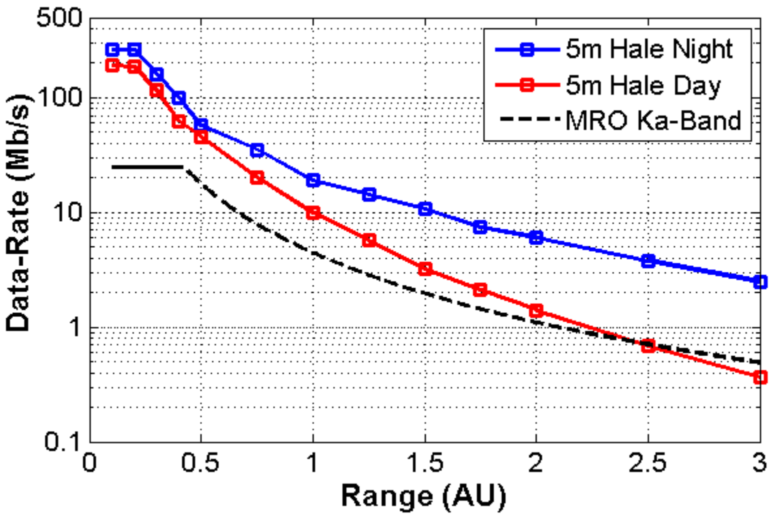


System detection efficiency for single pixel device

Marsili et al, *Nature Photonics* **7**, 210 (2013)

- WSi SNSPDs developed in 2012 by JPL and NIST
- Now fully commercialized
- System detection efficiency up to 93% @ 1550 nm
- Sub-Hertz intrinsic dark counts
- Maximum count rates of 20 Mcps (3 dB saturation)
- 80 ps FWHM timing jitter

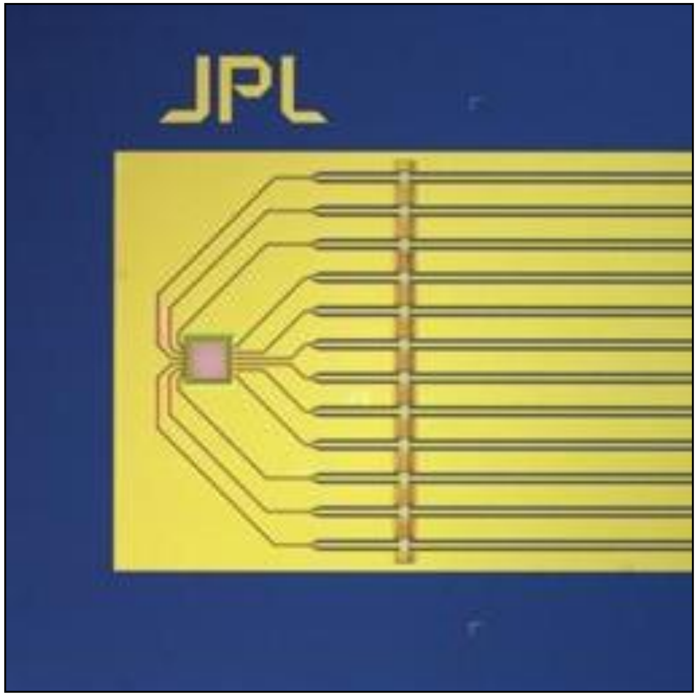
Why Deep Space Laser Communication?



Performance using 4W average laser power w/ 22 cm flight transceiver to 5m ground telescope

– **Currently:** Radio frequencies up to 40 GHz through the Deep Space Network (DSN)
– Future “optical DSN” promises **10-100x** more data than Ka-band RF links for equivalent mass and power on the spacecraft
– Will require larger (~ 10m) telescopes than current and past technology demonstration missions

Lunar Laser Communication Demonstration

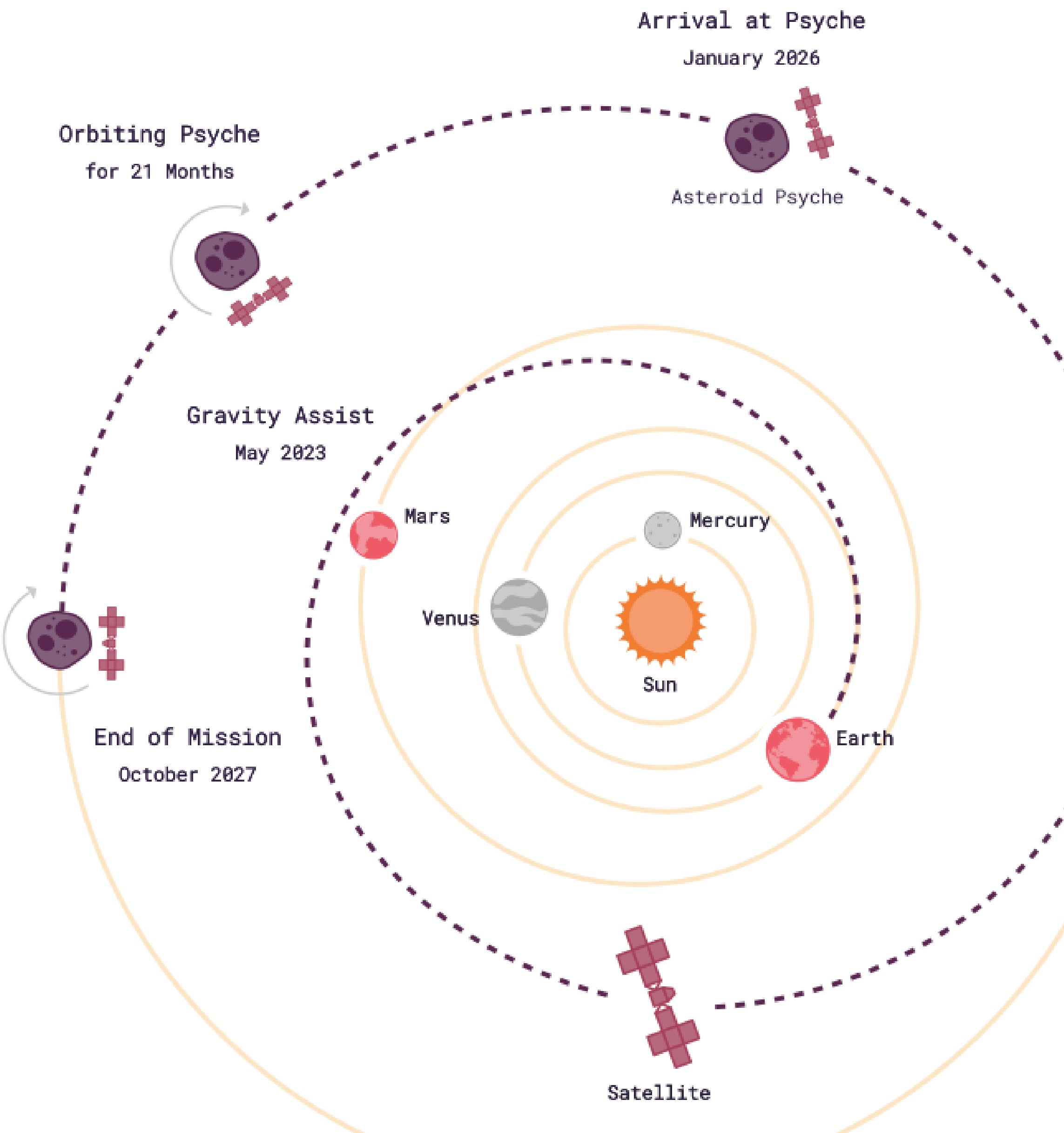


- Bidirectional laser communication demo from lunar orbit (400,000 km) at 1550 nm
- First demonstration of laser communication beyond earth orbit, 2013
- Uplink rates 10-20 Mbps, Downlink rates 39-622 Mbps
- Transmit Payload on LADEE Spacecraft (ARC) implemented by MIT-LL
- Managed by GSFC, Primary ground terminal implemented by MIT-LL using NbN SNSPD arrays
- Secondary ground terminal implemented by JPL using a WSi SNSPD array

NASA DSOC Project

Jet Propulsion Laboratory
California Institute of Technology

- DSOC is a technology demonstration mission planned to launch on board NASA's Psyche mission in 2022
- Psyche's trajectory takes it past Mars to the asteroid belt, where it will study the metal asteroid 16 Psyche
- The maximum Earth-spacecraft distance will be 2.77 AU



Pre-Decisional Information –
For Planning and Discussion Purposes Only

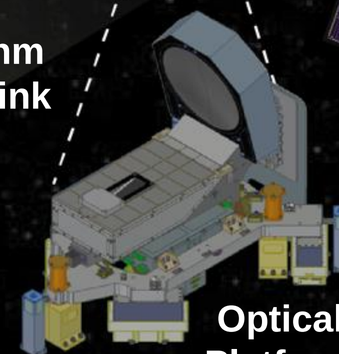
Deep Space Optical Communications (DSOC)

OBJECTIVES: Demonstrating optical communications from deep space (0.1 – 2.7 AU) at rates up to 267 Mbps to validate:

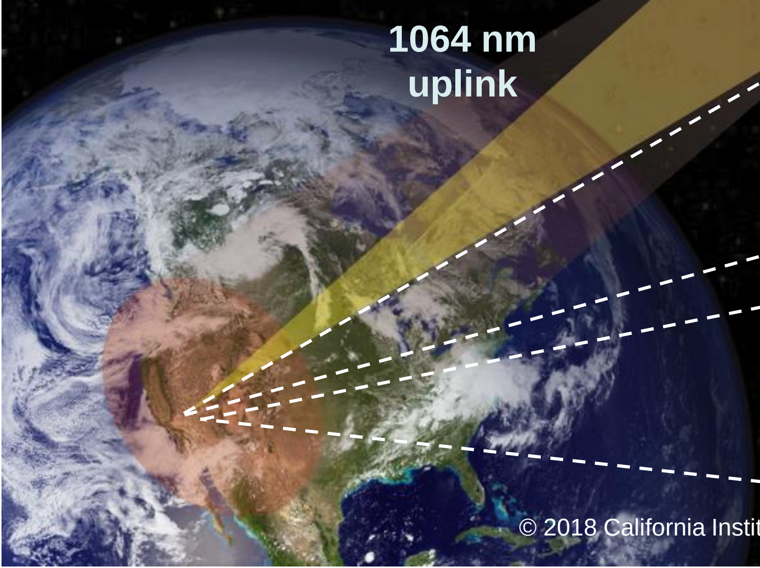
- Link acquisition laser pointing control
- High photon efficiency signaling

Psyche spacecraft

1550 nm downlink



Optical Platform Assembly
22 cm mirror
4 W laser power



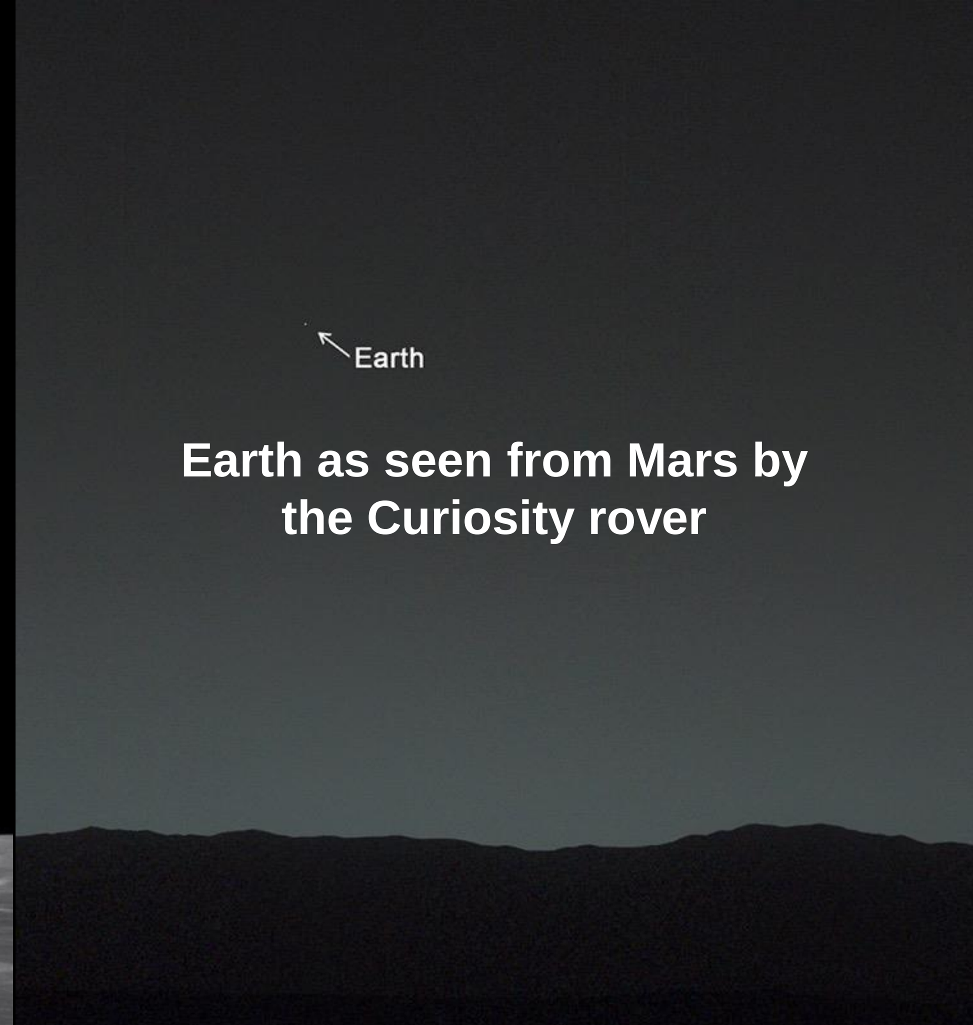
1064 nm uplink

Ground Laser Transmitter
Table Mtn, CA
1 m OCTL telescope
5 kW laser power

Ground Laser Receiver
Palomar Mtn, CA
5 m Hale telescope

Deep space challenges

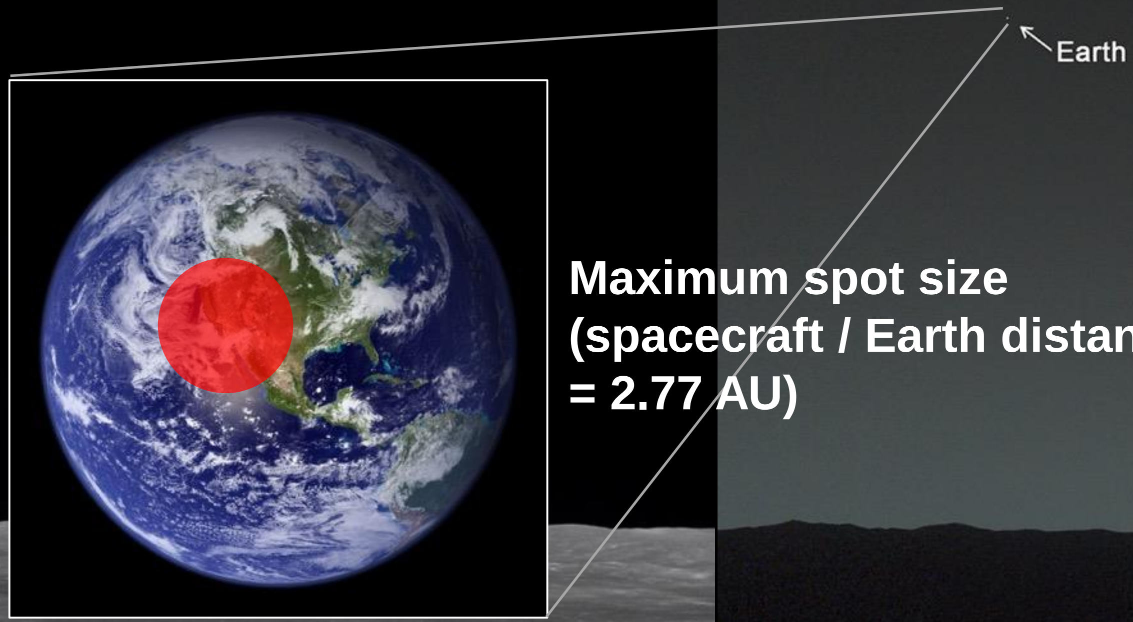
Earth as seen from the moon during the Apollo 11 mission



Earth as seen from Mars by the Curiosity rover

- **DSOC key challenge - huge increase in link distance from LLCD** (90 × to > 900×)

Deep space challenges



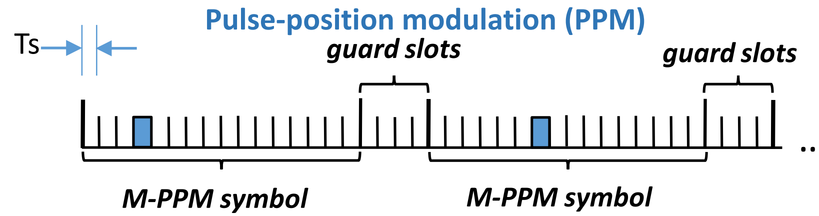
Maximum spot size (spacecraft / Earth distance = 2.77 AU)

- **DSOC key challenge - huge increase in link distance from LLCD** (90 × to > 900×)
  - Increase transmitter laser power (4 W vs. LLCD 0.5 W)
  - Decrease beam divergence (8 μrad vs. LLCD 16 μrad): **<u>introduces pointing challenge</u>**
  - Increase flight and ground detector sensitivity

DSOC Challenges

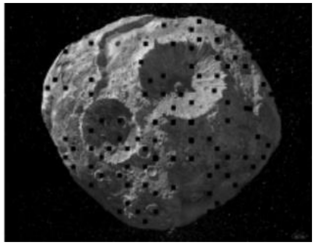
DOWNLINK

- **Implement photon-efficient signaling (emerging CCSDS Standard for High Photon Efficiency)**
  - **High peak-to-average power ratio (160:1)**
  - **Pulse-position-modulation (PPM)** with variable orders (M = 16, 32, 64, 128; Ts = 0.5,1,2,4,8 ns)
  - **Slot/symbol/frame synchronization features**: Inter-symbol guard time (ISGT) slots (M/4) and codeword sync marker (CSM) sequences
  - **Near-channel-capacity forward error correction**: serially concatenated convolutionally coded PPM (SC-PPM) with variable code rates (1/3, ½, 2/3)
  - **Interleaving for fading mitigation**: convolutional channel interleaver
    - Distributes deep fades across codewords to allow decoder to work (~3 dB recovered)
    - Designed with 2.7 sec depth for all data rates (based on pointing jitter estimates)
  - **Lower data rates for far ranges** with variable symbol repeat factors and slot-widths (0.5 – 8 ns) - enable multitude of rates



Fading causes burst outages

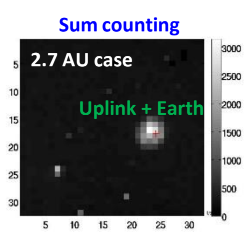
Decoder corrects more errors spread across codewords by interleaver

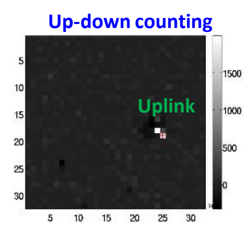


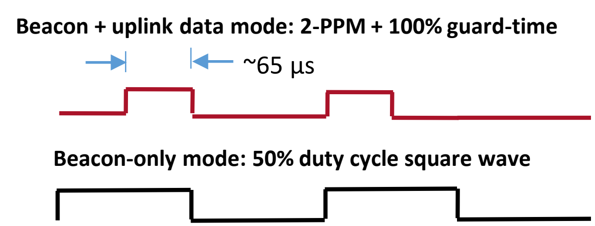
UPLINK

- **Uplink modulation supports**
  - "Up-down" counting for background subtraction
  - Low data-rate (1.6 kb/s) out to 1 AU with low density parity check (LDPC)

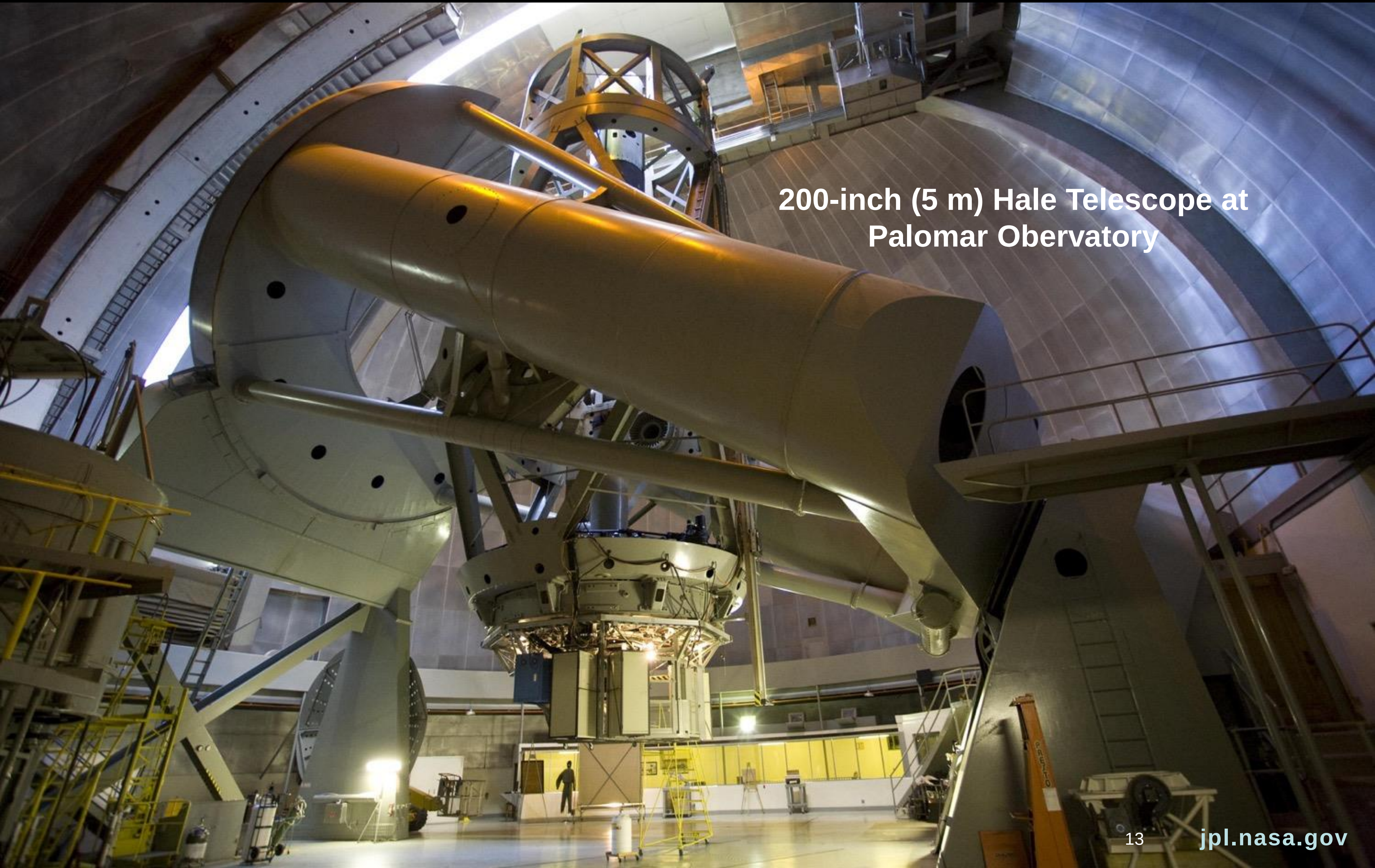
Meet deep space challenge with photon-efficient signaling





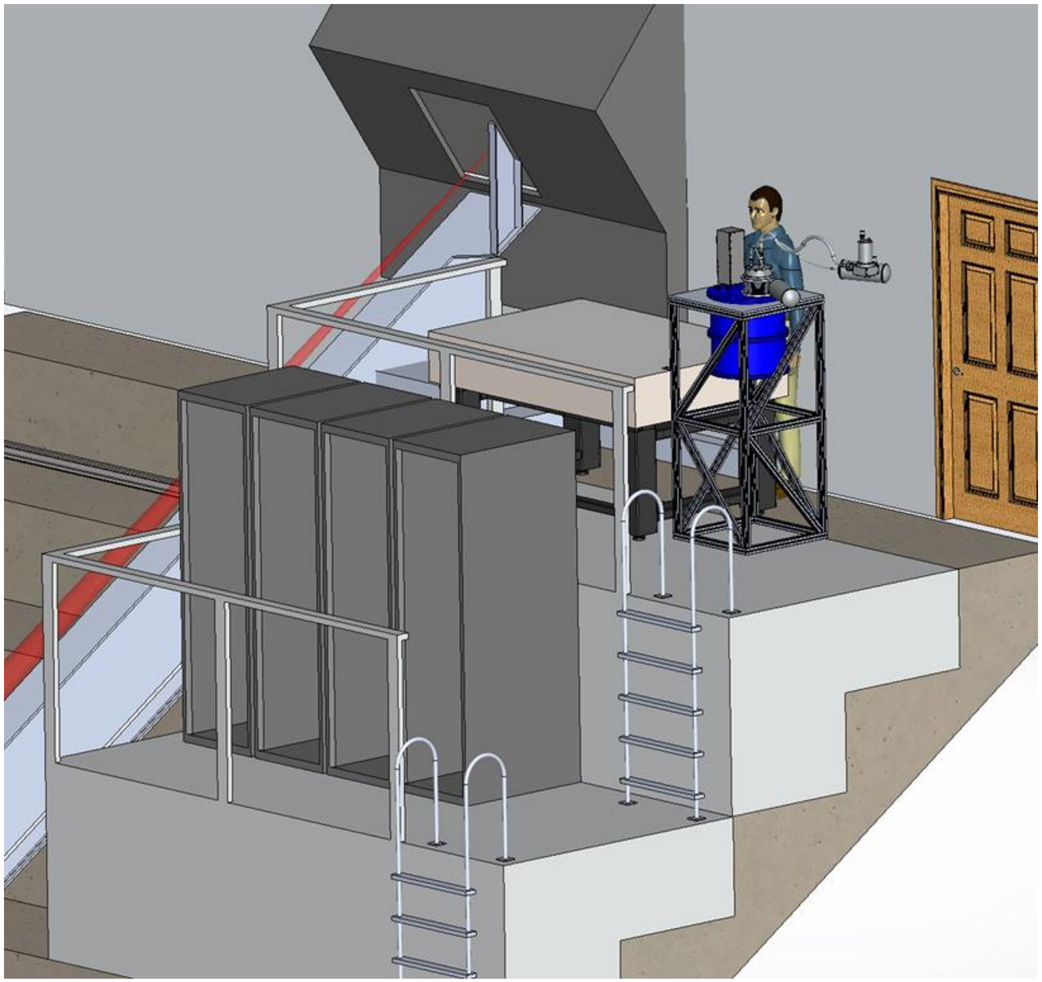


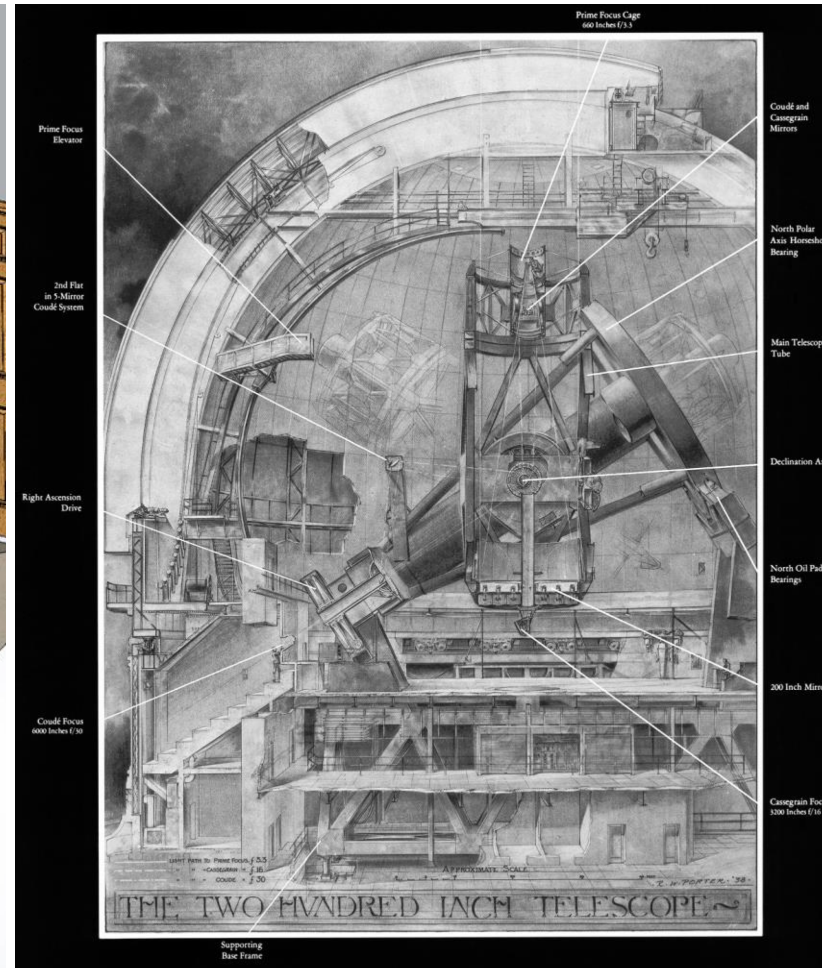
Increasing receiver sensitivity: collection area



Accomodation at Palomar Observatory

- Cryogenic detector instrument planned for Coude focus of Hale telescope
- Does not require cryostat to move with the telescope

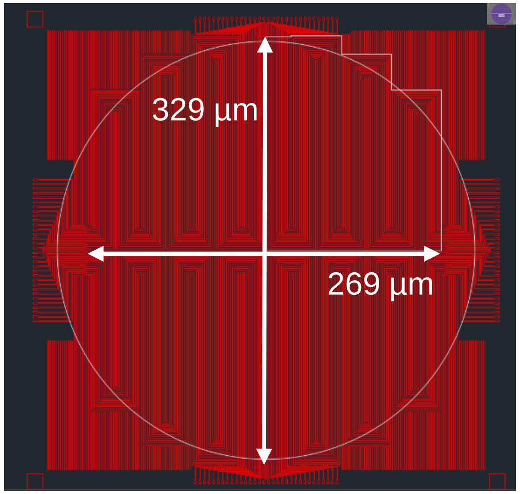




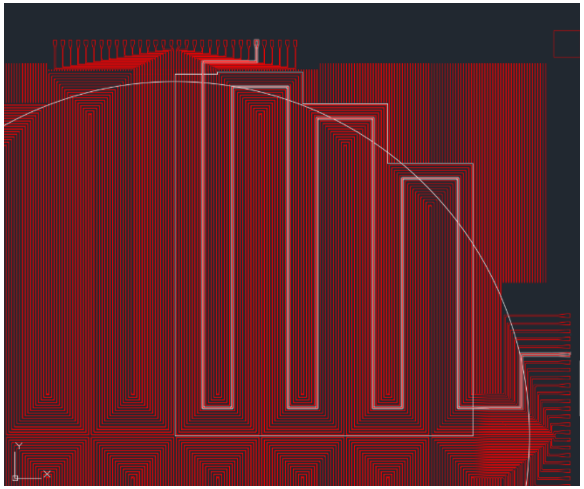
Concept for cryostat location at Palomar 200-inch telescope

64-Pixel SNSPD for Ground Receiver

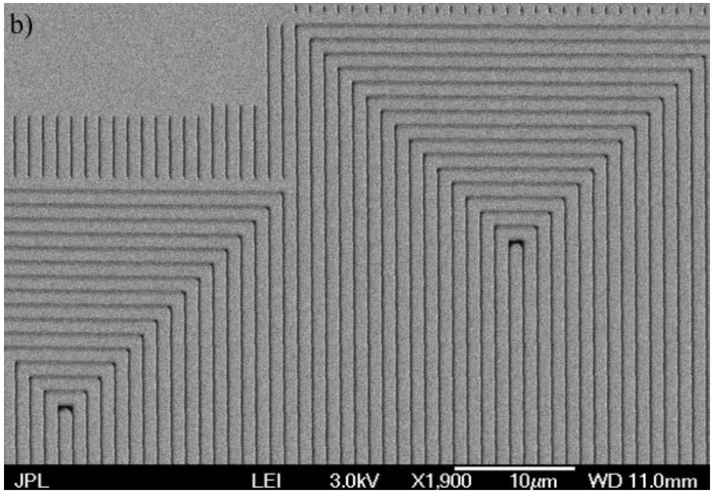
- SNSPD planned for DSOC Ground Laser Receiver at 200 inch Palomar telescope (5.1 m)
- 64-element WSi SNSPD array with >79,000 μm^2 area (equiv. to 318.5 μm diameter)
- Divided into four spatial quadrants for fast beam centroiding
- 160 nm WSi nanowires on 1200 nm pitch – each wire ~1 mm in length (~7000 squares)
- Free-space coupling to 1 Kelvin cryostat, with cryogenic filters and lens
- 78% system detection efficiency at 1550 nm
- < 80 ps FWHM timing jitter
- ~1.2 Gcps maximum count rate



CAD Design of SNSPD focal plane array



CAD Design showing one of 16 individual sensor elements per quadrant



Electron Microscope Image of Nanowire Structure

Readout Electronics

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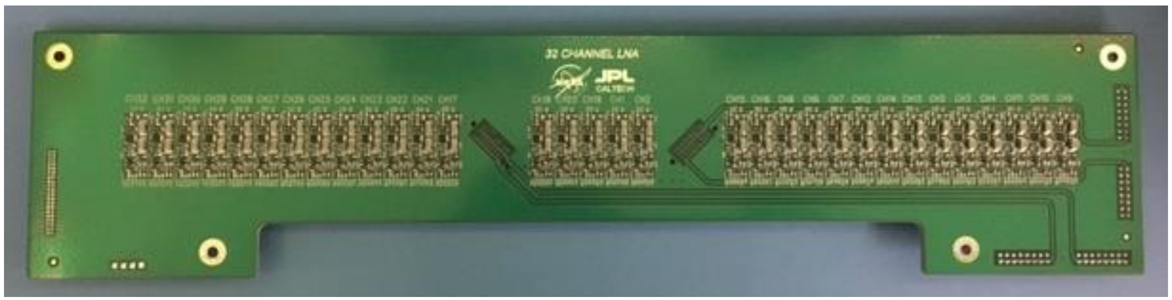
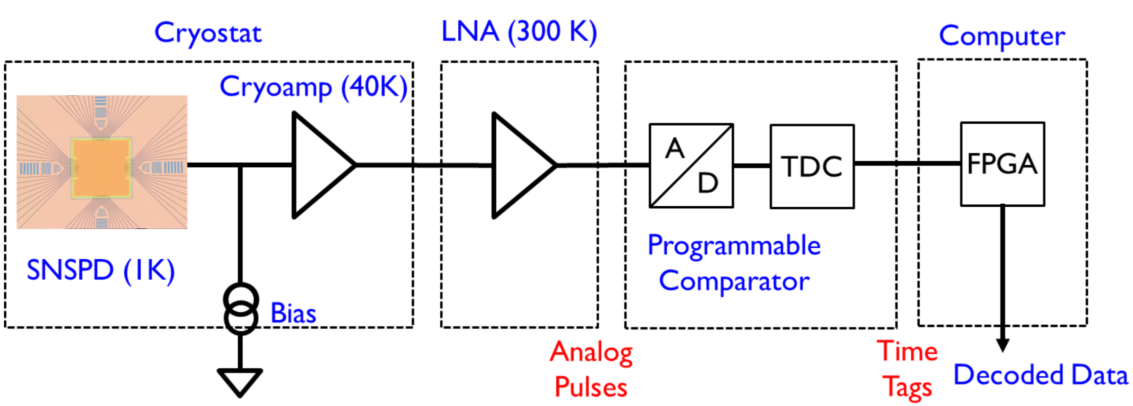
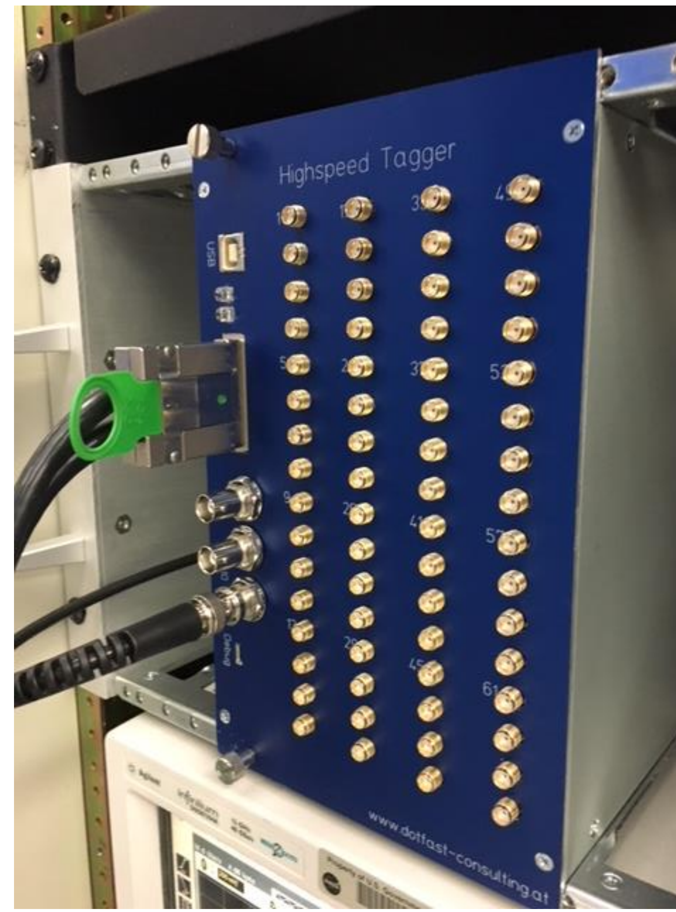
- Worked with industry on 64-channel TDC capable of streaming 900 Mtags / sec over PCIe
- Each nanowire sensor element has its own dedicated readout channel
- DC-coupled cryogenic amplifiers used at 40 K stage of cryostat



40 Kelvin Cryogenic Amplifier Board

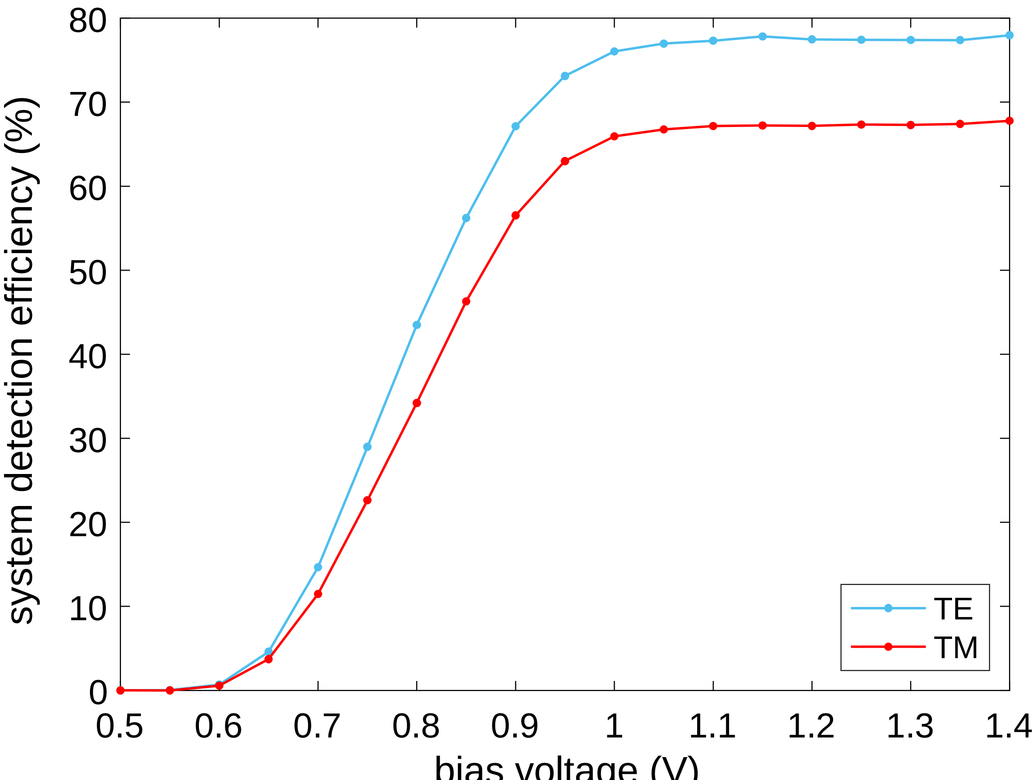




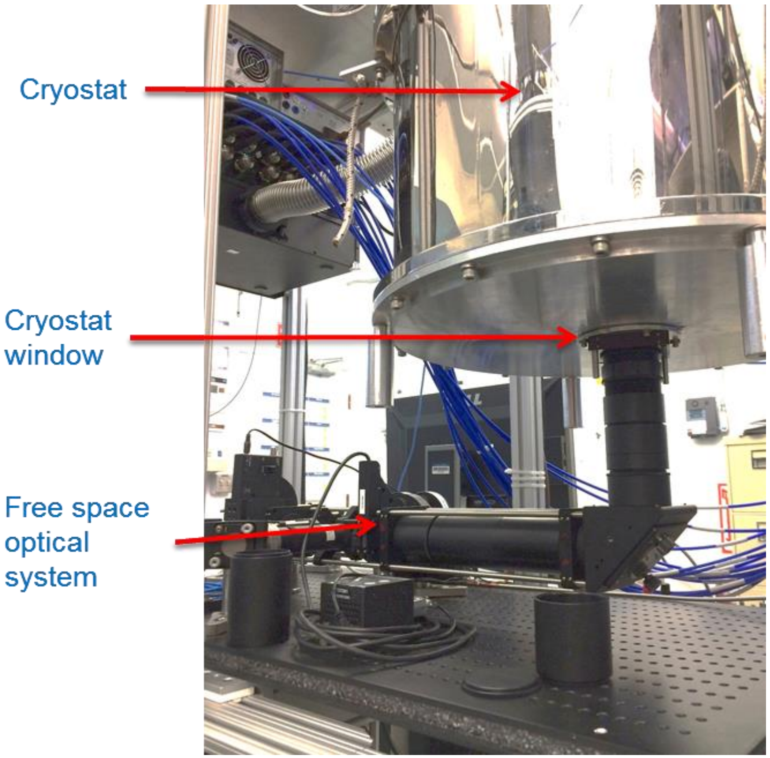
Streaming 64-channel time-to-digital converter

System Detection Efficiency

- 78% System Detection Efficiency in TE Polarization, 68% in TM
- Measured at low flux (~100 kcps) with lens outside the cryostat (f/4 beam)
- Measured with ~110 µm diameter spot in center of one 16-pixel quadrant
- Prototype array has 62 out of 64 pixels working – screening arrays to find 64 perfect wires



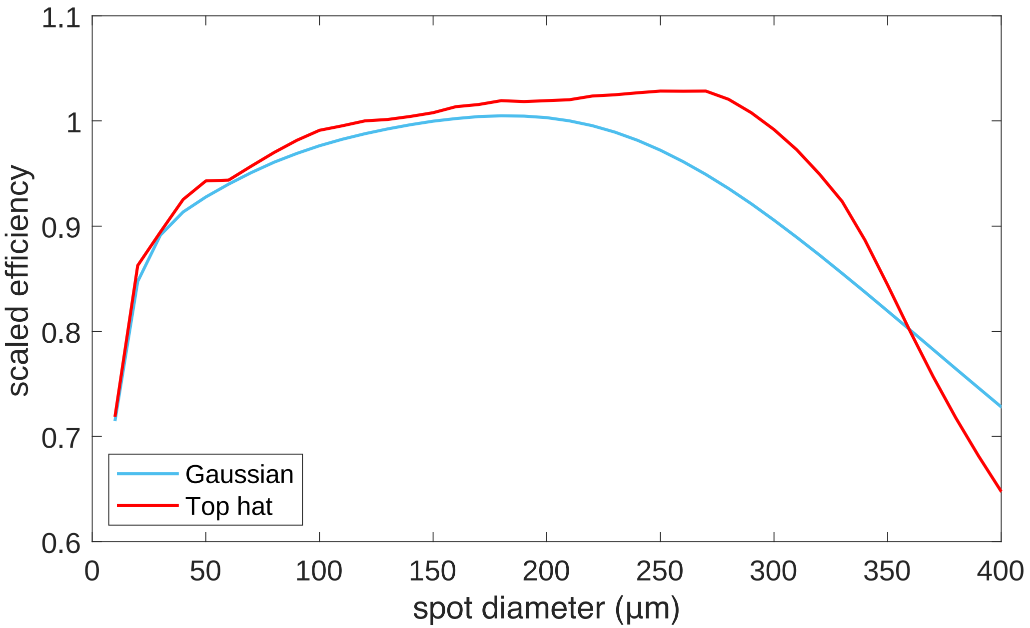
System Detection Efficiency of SNSPD Array



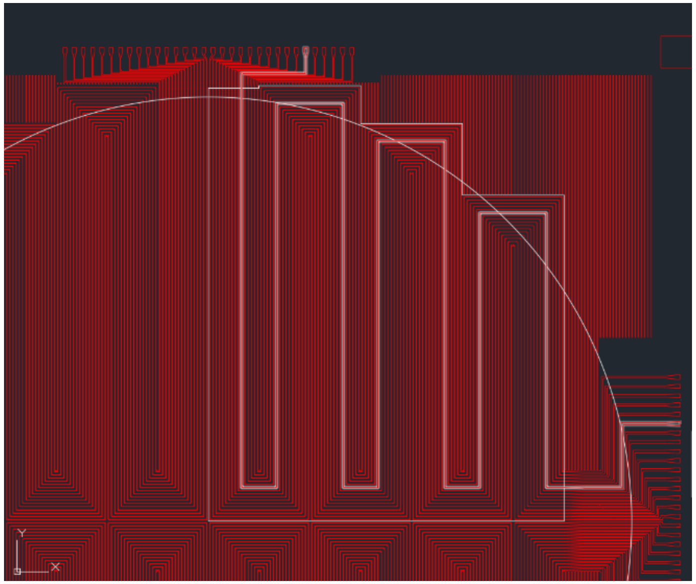
Free-space coupling into cryostat

Efficiency as a Function of Spot Size

- Used nanowire layout to estimate efficiency dependence on spot size for TE polarized light
- Optimal spot size is between 90 – 250 µm
- Small spot sizes sample bends and horizontal nanowire regions
- Large spot sizes are vignetted by the edges of the detector
- Such models can be used to perform real-time estimates of spot size with non-imaging array

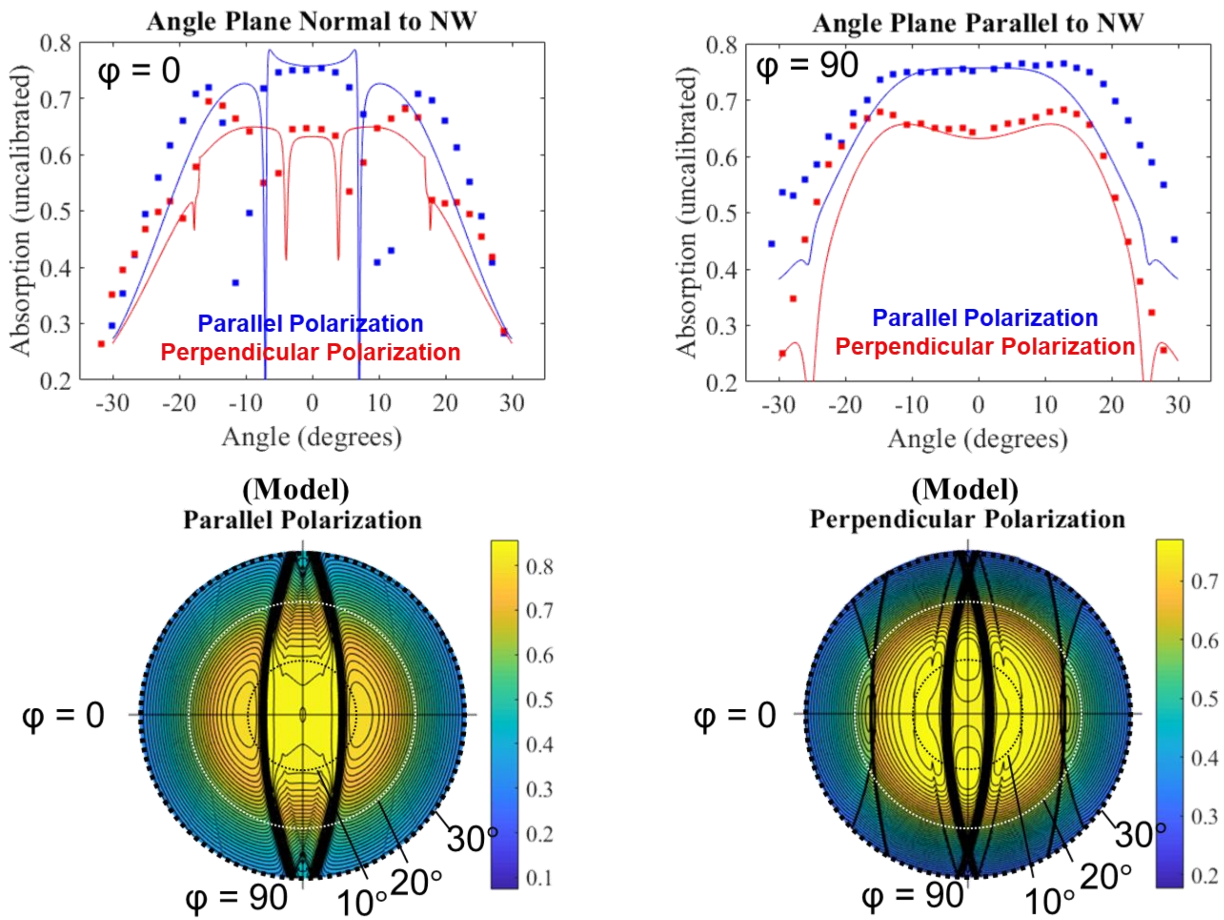


Modeled efficiency derating as a function of spot size



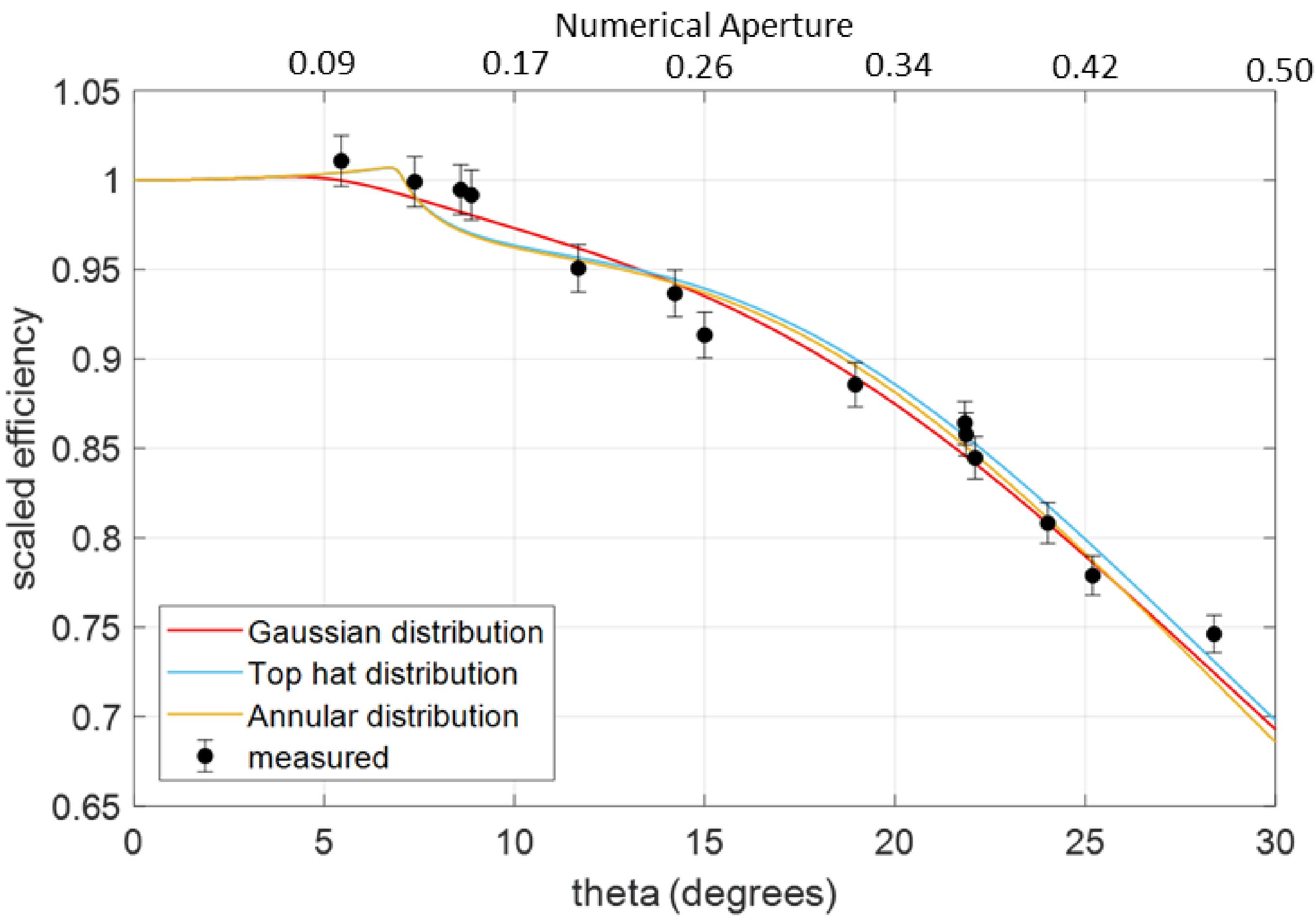
Layout of SNSPD array

Angular Dependence of Efficiency



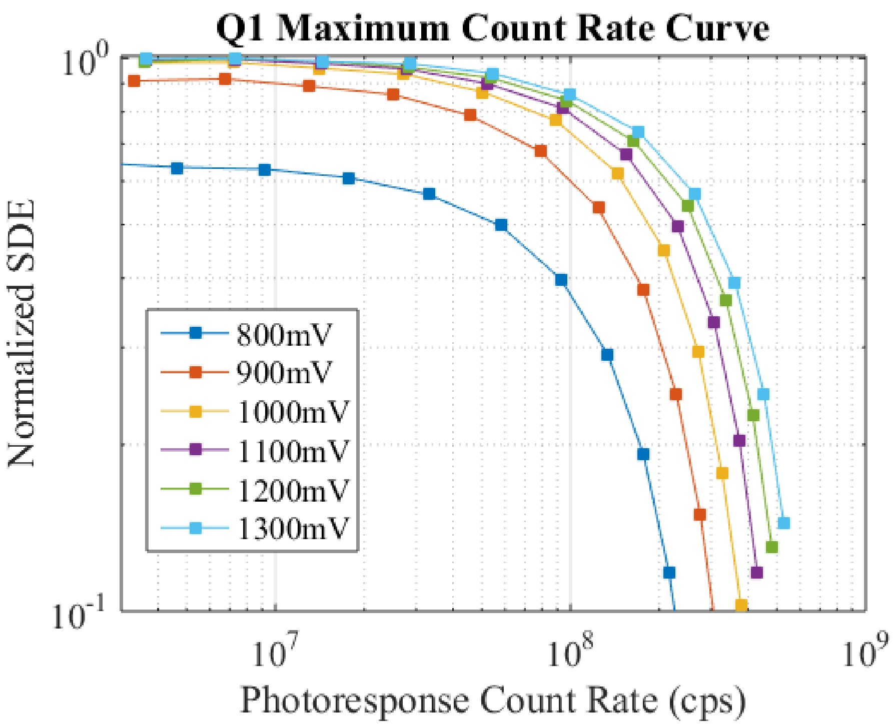
- On-chip cavity structure limits angular acceptance of detector beyond ~20 degrees
- Measured by displacing collimated beam across a cryogenic lens
- Experiments show excellent agreement with RCWA simulations

Numerical Aperture

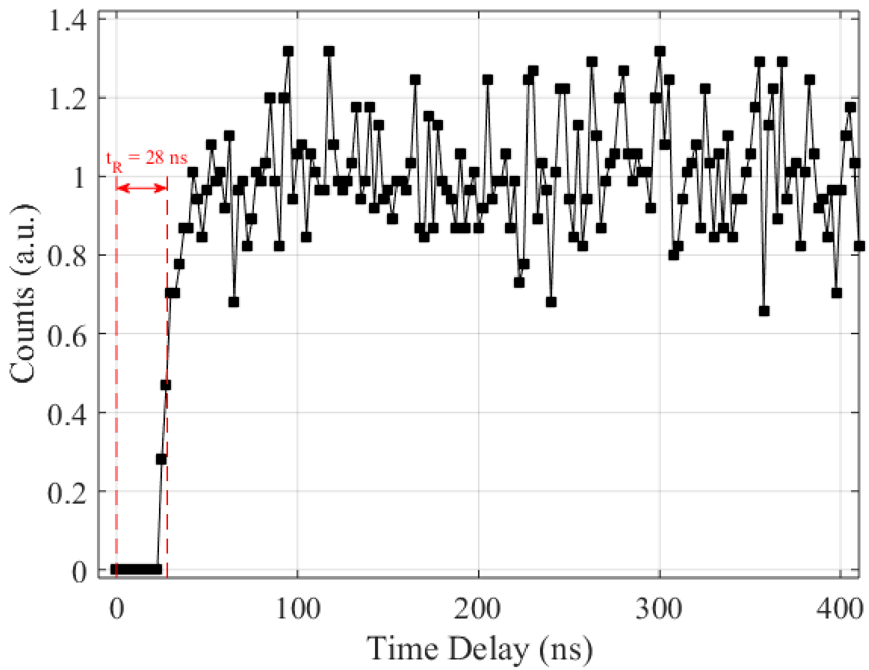


- Limited angular acceptance determines finite numerical aperture of SNSPD
- 10% drop in efficiency at 0.32 NA, >20% drop at 0.42 NA
- Tradeoff in cavity design between collimated beam efficiency and angular acceptance

Maximum Count Rate



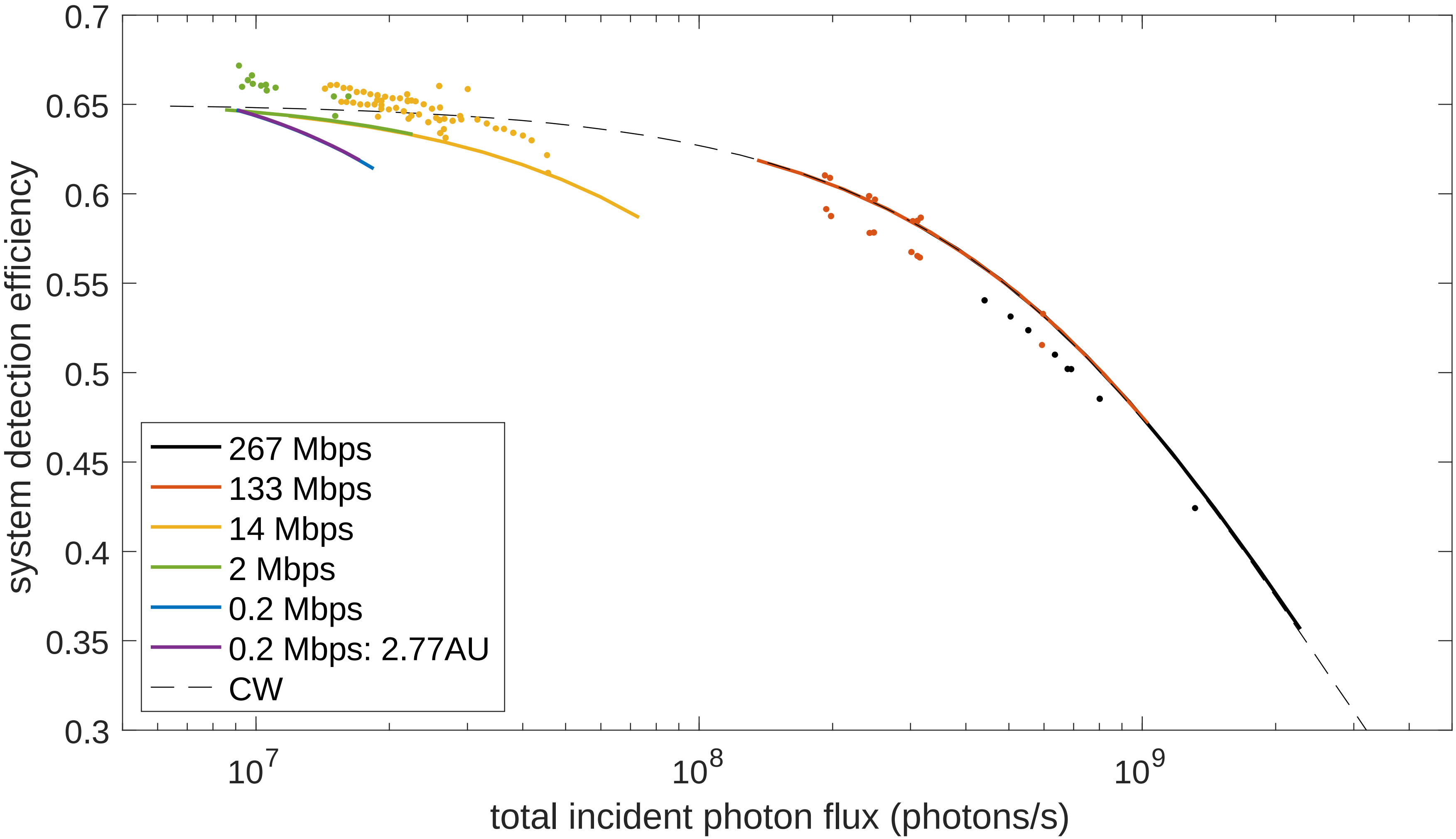
Maximum count rate measured for one 16-channel quadrant



Interarrival time histogram showing 28 ns dead time, no afterpulsing

- MCR measured with beam centered on a single quadrant due to count rate limitations in TDC
- 120 – 300 Mcps 3dB point per quadrant
- Scales to 465 – 1160 Mcps across 62 pixels
- Present total counting rate is limited to 900 Mcps by time tagging electronics

MCR vs Signaling Format



- MCR scales differently for different PPM data formats
- Data is for PPM-encoded communication links, scaled for expected efficiency in DSOC

Timing Jitter

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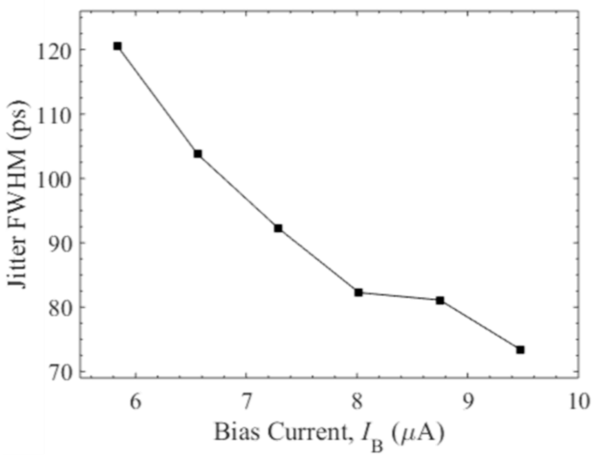
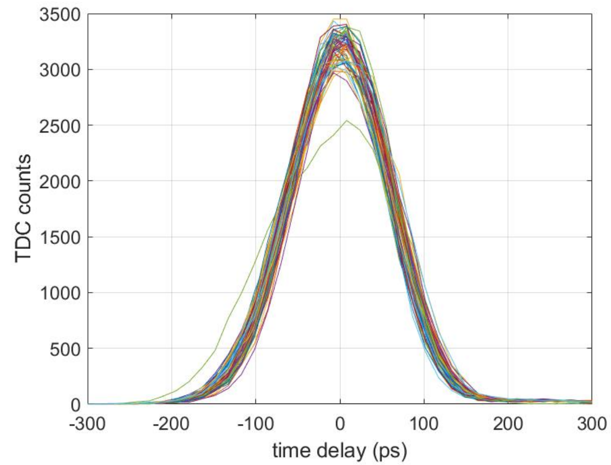


Timing jitter of one SNSPD channel, measured with oscilloscope



Instrument response function for each pixel, histogram of TDC time tags

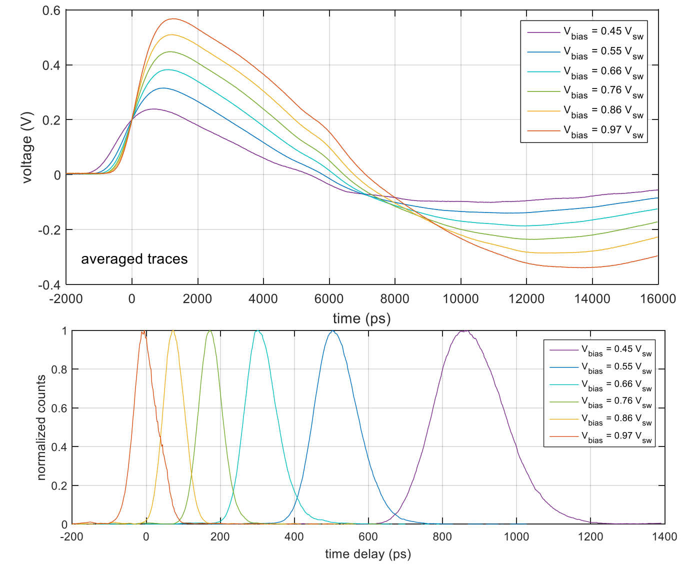
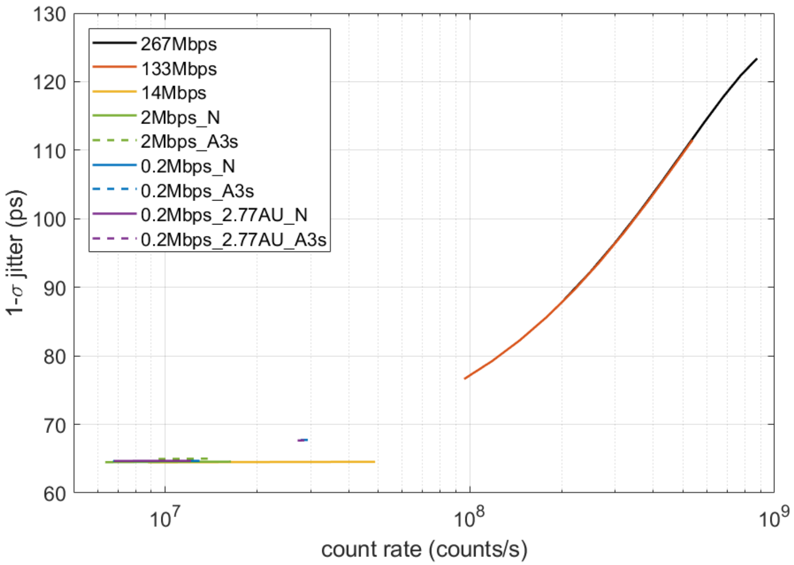


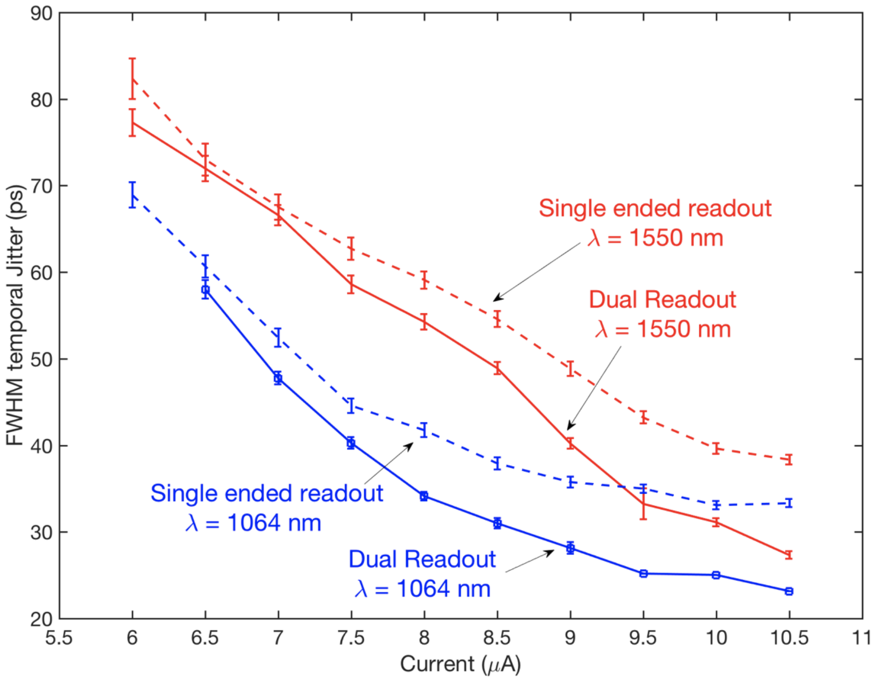
Illustration of Temporal Walk



Estimated timing jitter as a function of count rate for different signaling formats

- Total system jitter < 80 ps FWHM at low flux rates.
- TDC jitter alone ~75 ps FWHM.
- Jitter dominated by temporal walk at high count rates, due to fluctuating pulse height
- Removal of walk is possible with constant fraction discriminator (analog or firmware)

Intrinsic Limits of Timing Jitter



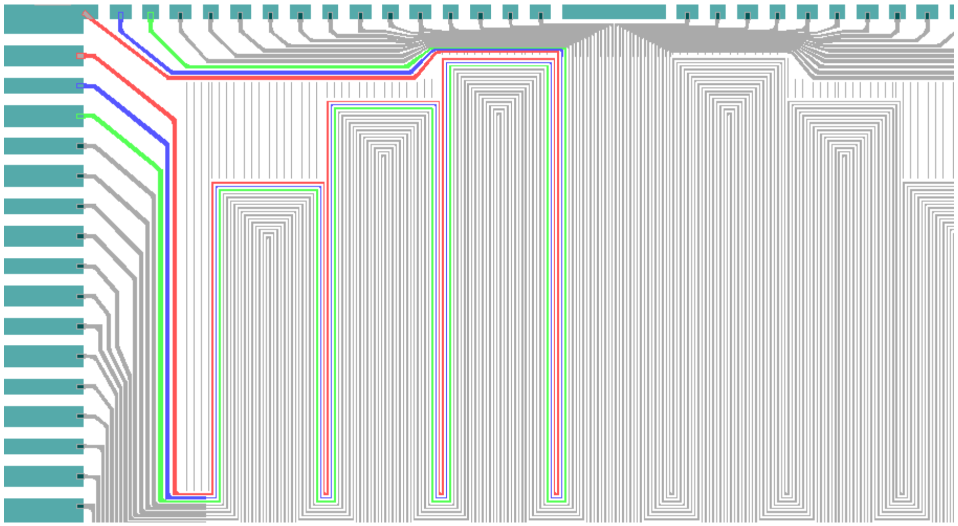
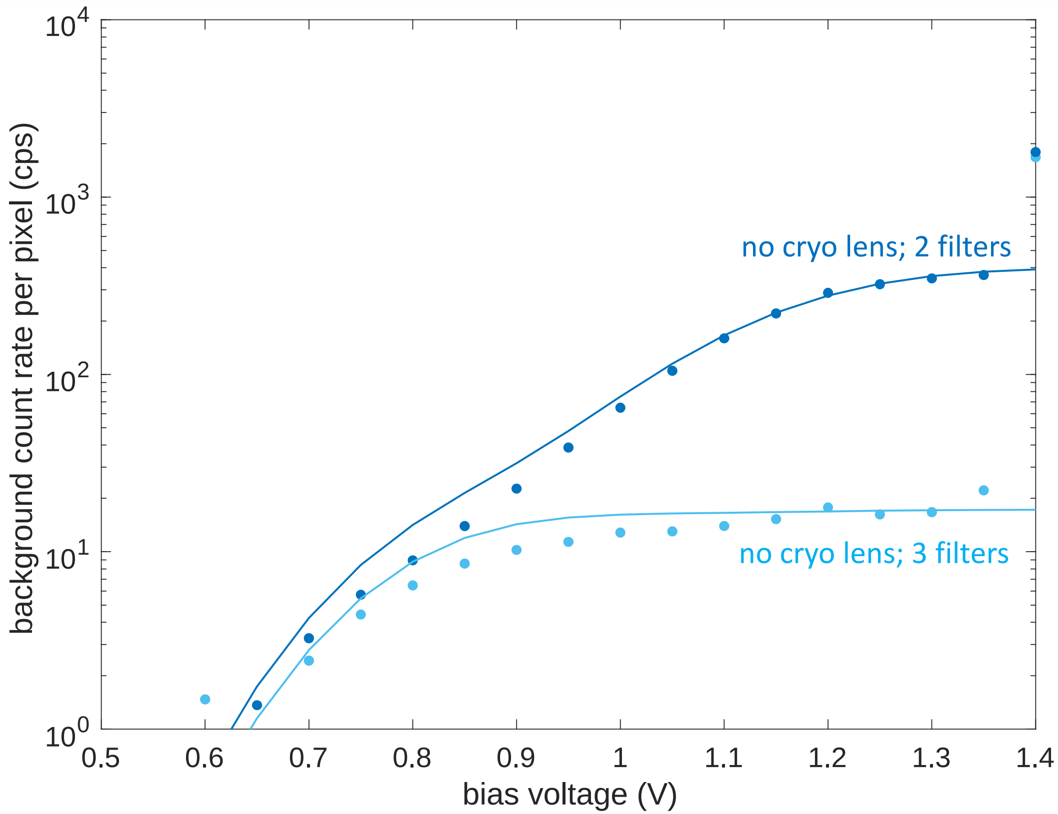


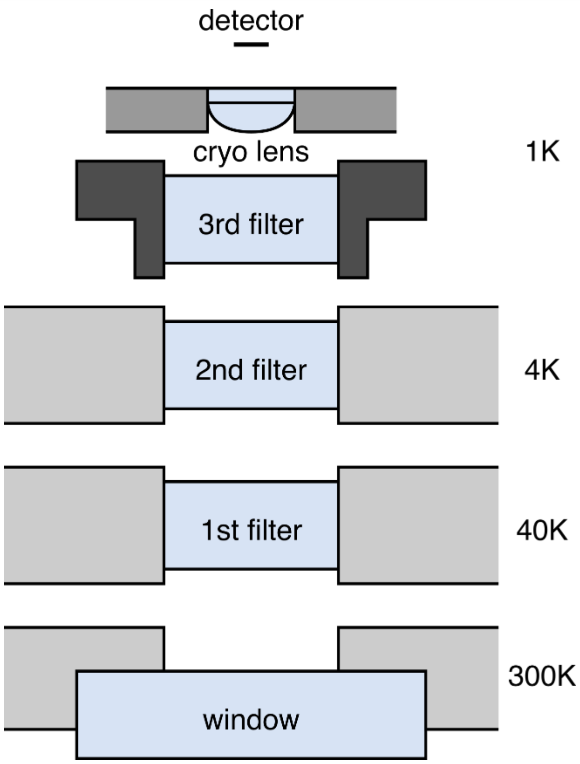
Illustration of Differential Version of DSOC-sized Array

- Using a low-noise cryogenic amplifier and differential readout, demonstrated jitter < 30 ps FWHM in a WSi device similar to the DSOC array
- Photon energy dependence shows significant effect of intrinsic jitter in WSi nanowires

Dark Count Rate



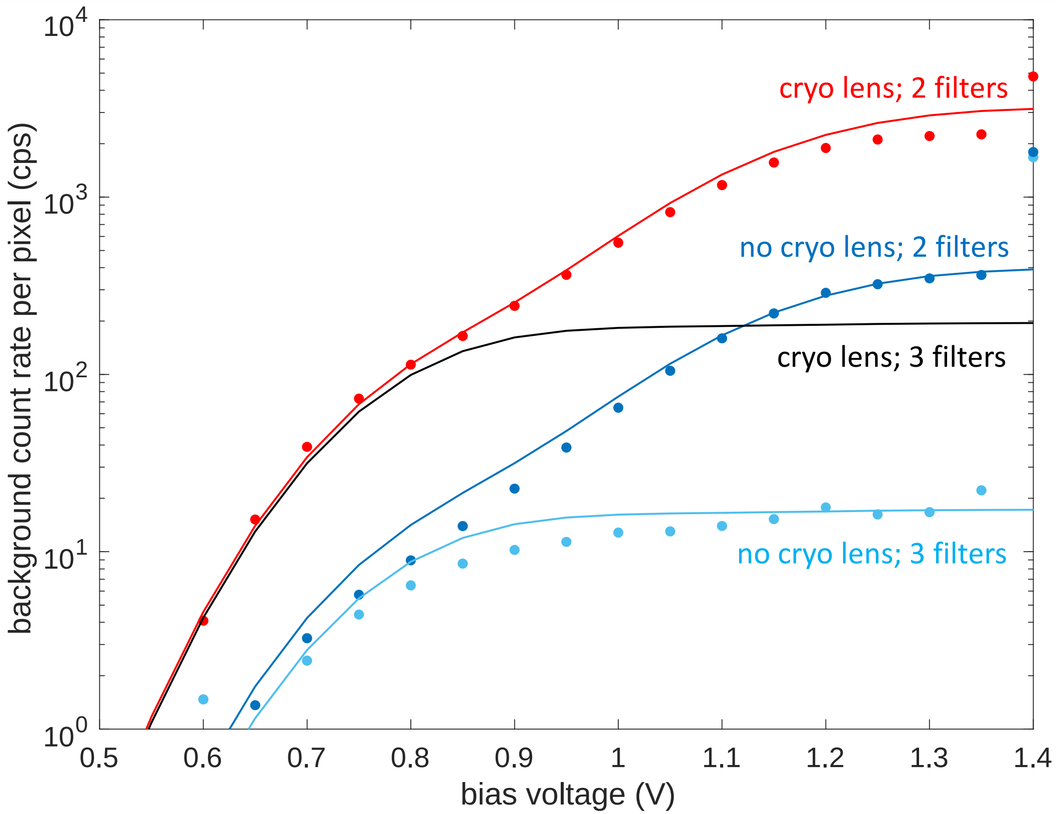
System false count rate with model



Schematic of cryogenic filter setup

- Cryogenic filters used to block the IR blackbody radiation from 300 K optical system
- Cryogenic QCL measurements show SNSPD is single-photon sensitive to 4200 nm
- ~1000 cps false count rate across array with lens outside cryostat (16 cps per pixel)
- Expect ~10 kcps across array with cryogenic lens
- ~ 1 cps dark count rate measured across array with 4 K filter port blanked

Dark Count Rate



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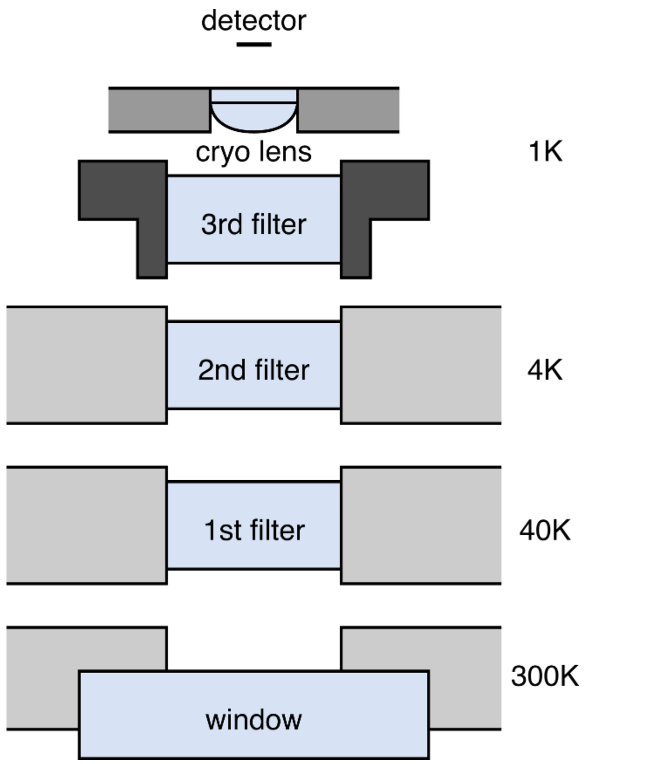

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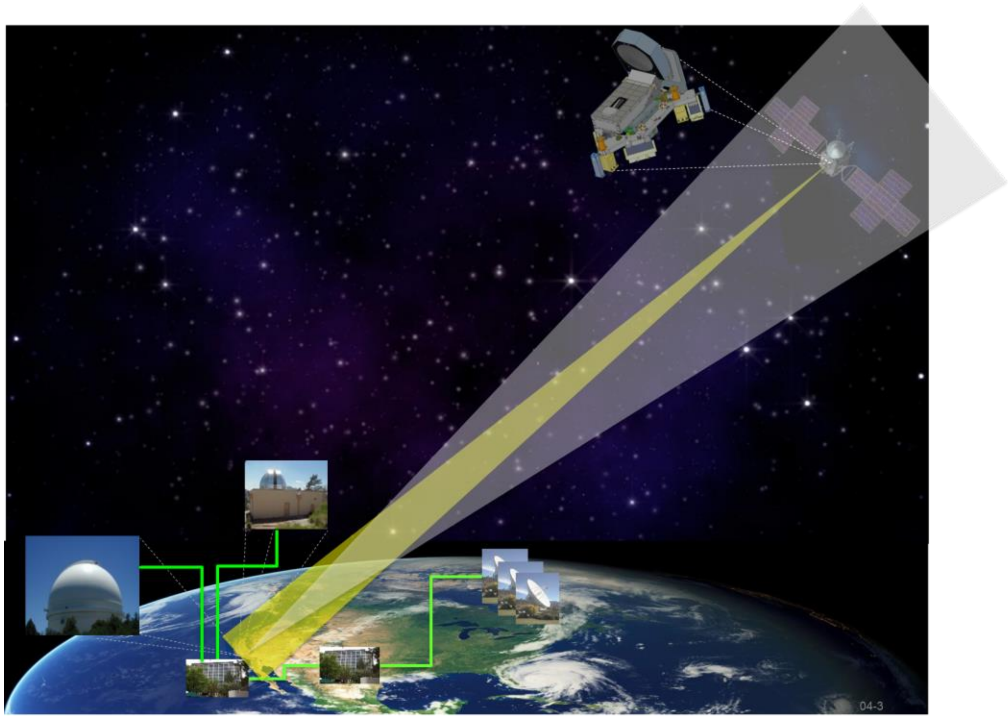
DSOC Project Summary

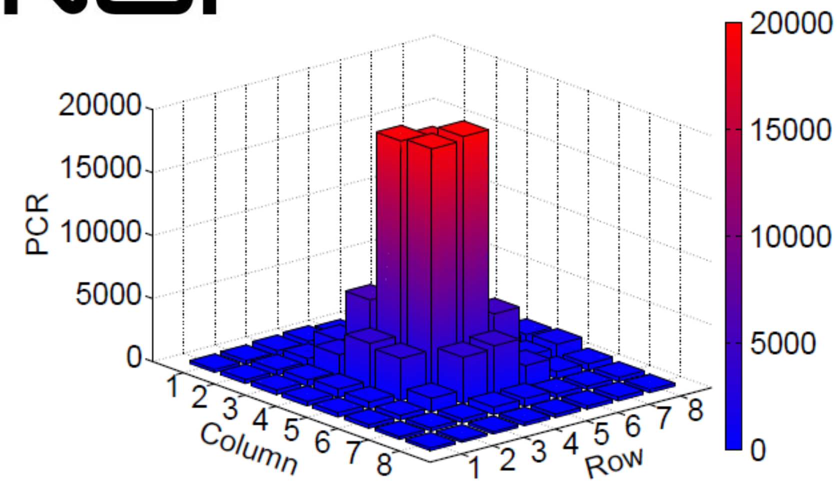
- Deep space laser communication offers 10-100x higher data rates than Ka-band radio for equivalent mass and power on the spacecraft
- NASA DSOC project will provide the first demonstration of laser communication from beyond lunar orbit, with free-space links up to ~400 million km
- 64-pixel SNSPD arrays are a key technology for the ground receiver at Palomar observatory
- Future optical Deep Space Network will require ~10x larger and faster SNSPD arrays

Packaged SNSPD Array

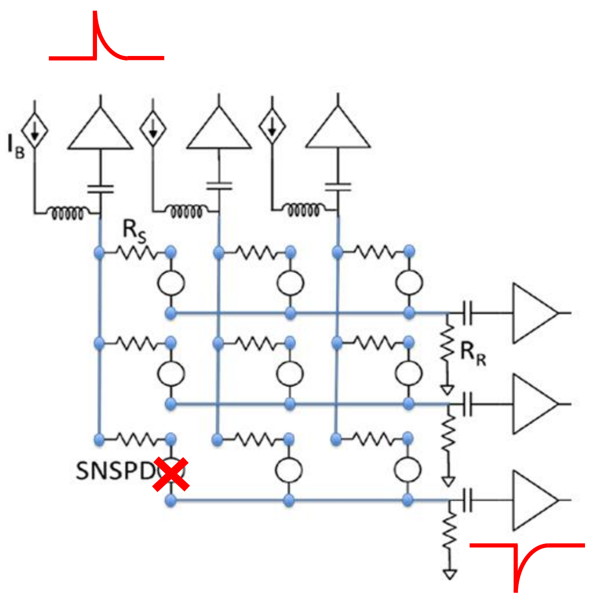


DSOC Project Concept

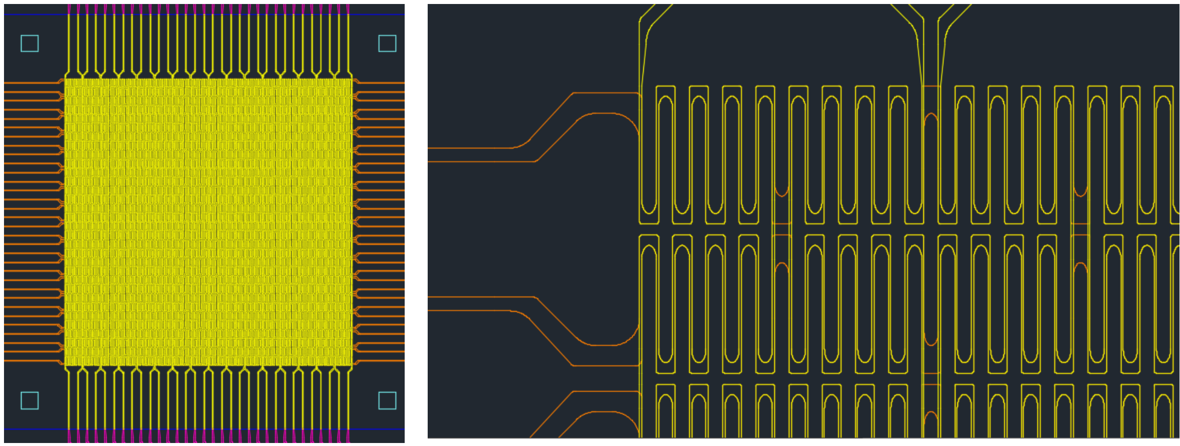
Prospects for Imaging Arrays



- 64 pixel (8 x 8) sparse WSi SNSPD array demonstrated for time-correlated imaging
- Row-Column readout strategy allows 64 pixels to be read out using 16 lines
- Kilopixel 32 x 32 array in development using “thermal” row-column scheme
- Close collaboration between JPL and NIST
- Potential applications include quantum imaging, biomedical imaging, photon counting lidar, imaging quantum receivers



Operating Concept

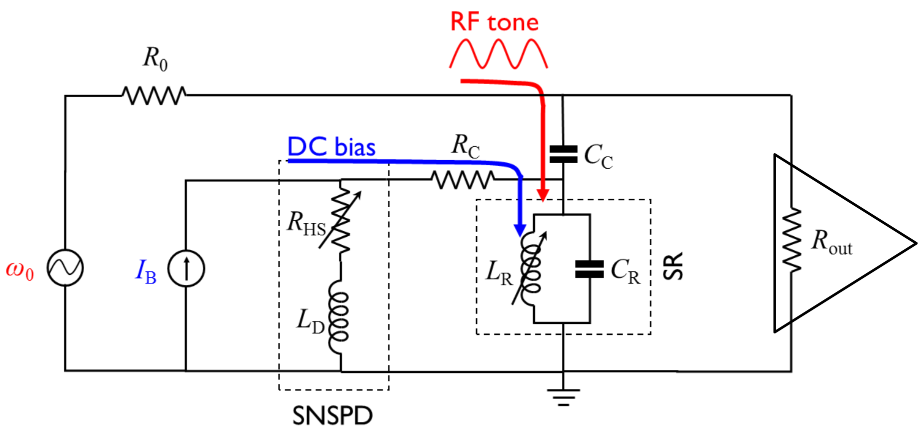


Example designs for 32 x 32 thermal row-column SNSPD imager

Other Multiplexing Strategies

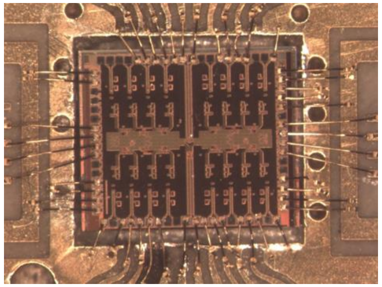
Jet Propulsion Laboratory
California Institute of Technology

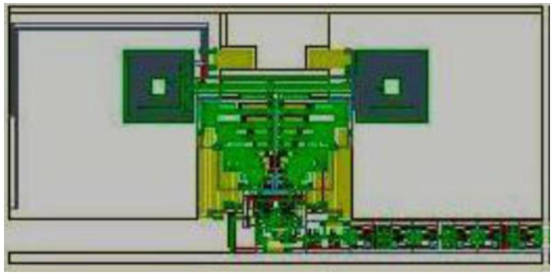
Frequency Domain



- Similar trade space to MKIDs

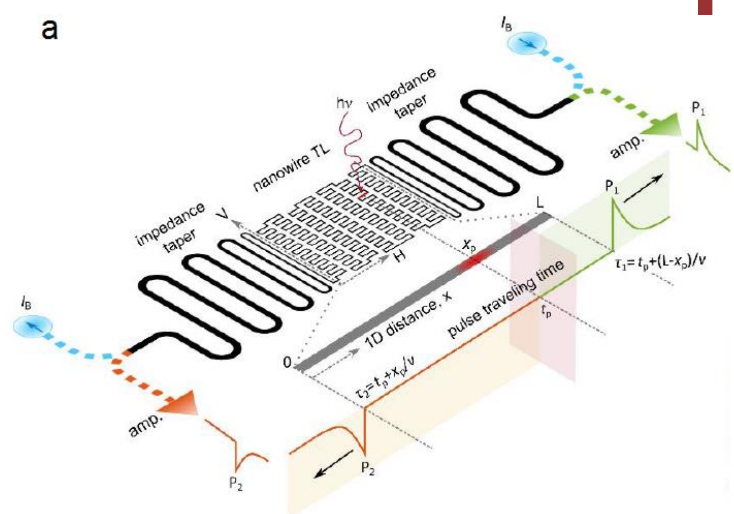
Cryogenic ROICs



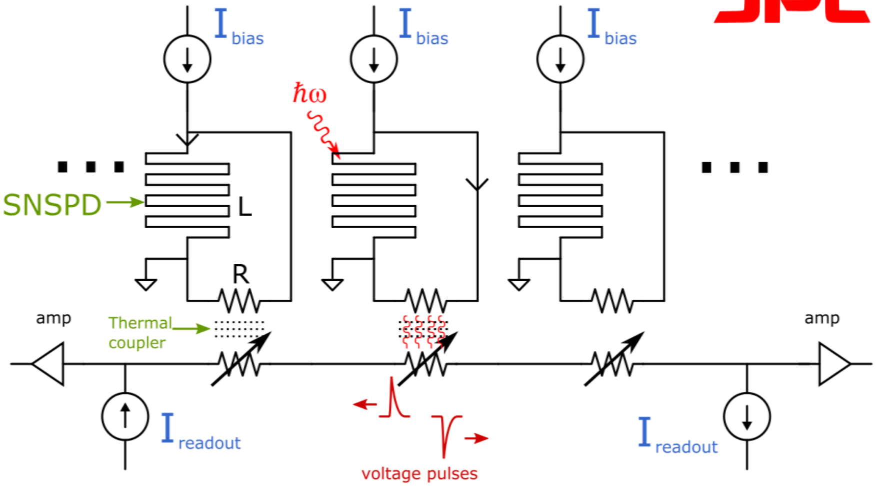


- SiGe and superconducting SFQ readout circuits are under investigation

Position Sensitive Nanowire

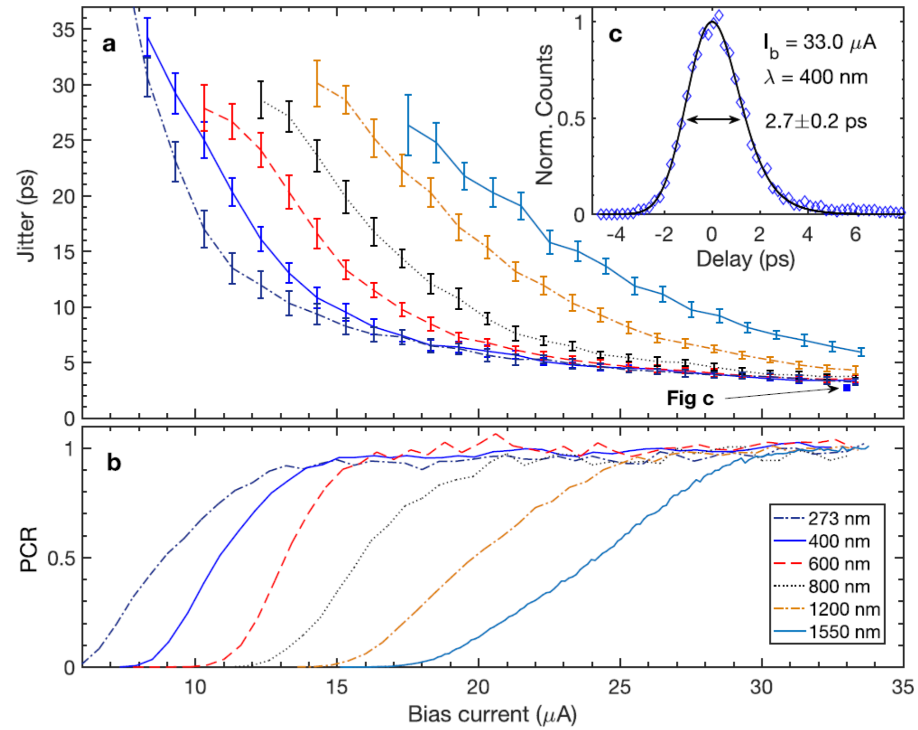


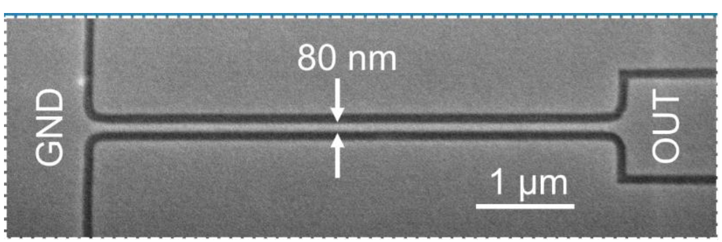
Thermally Coupled Imager



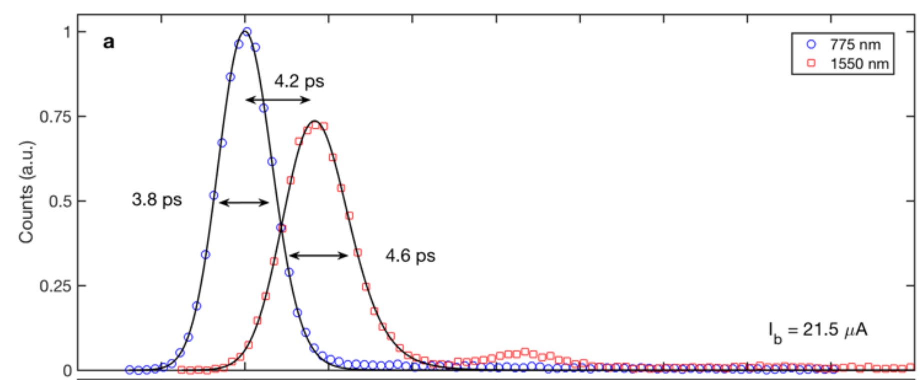
Ultra-high time resolution in SNSPDs

- Collaborative research project between MIT, JPL, and NIST has reduced timing jitter in SNSPDs from ~15 ps to as low as 2.7 ps FWHM
- Achieved through high switching current and low noise readout
- NbN Detectors were fabricated at MIT and measured at JPL
- Devices had small active area to eliminate geometric jitter, but differential readout has been demonstrated to achieve low jitter on large-area devices





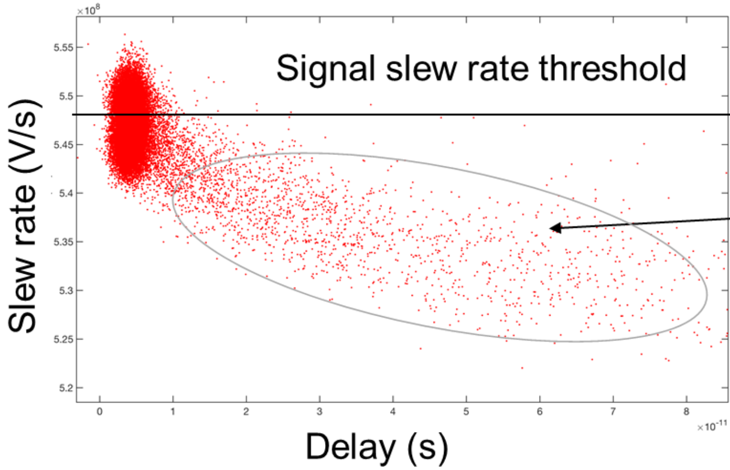
Specialized low-jitter NbN SNSPD



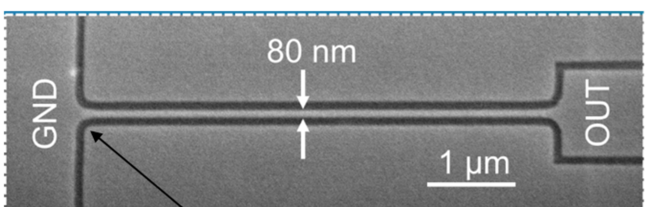
Dependence of timing jitter on photon energy

Korzh et al, arXiv 1804.06839 (2018)

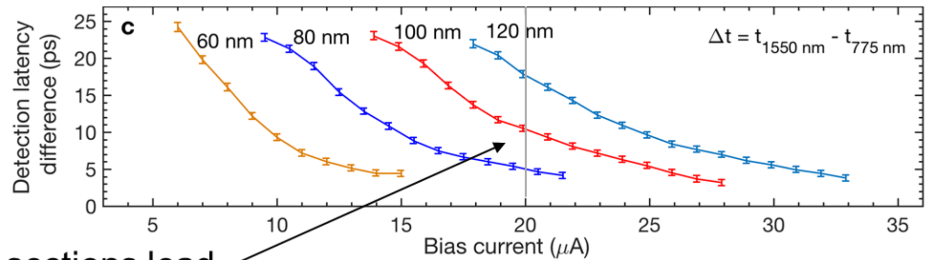
Ultra-high time resolution in SNSPDs

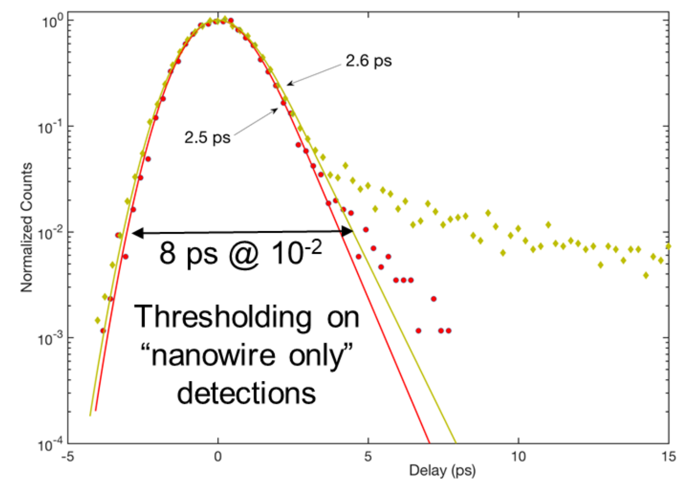


Wider sections lead to larger latencies



Hotspot resistance is lower in tapering sections
→ lower slew rate
Possible to gain information about position of detection



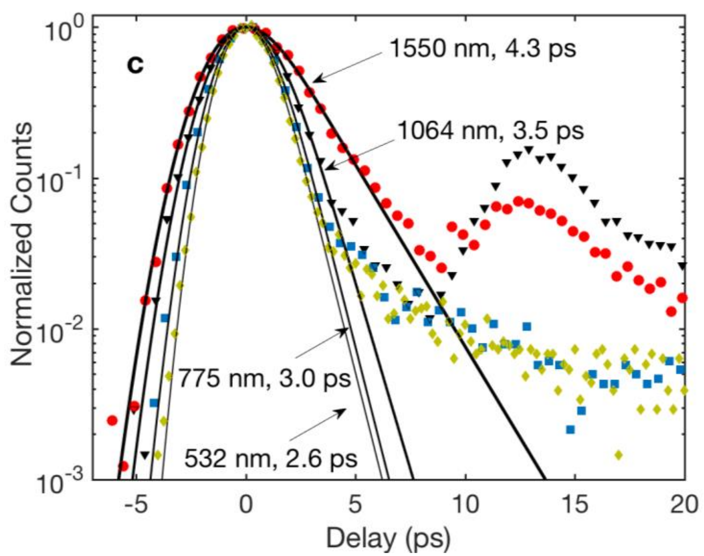


Important to concentrate detections away from tapers and bends

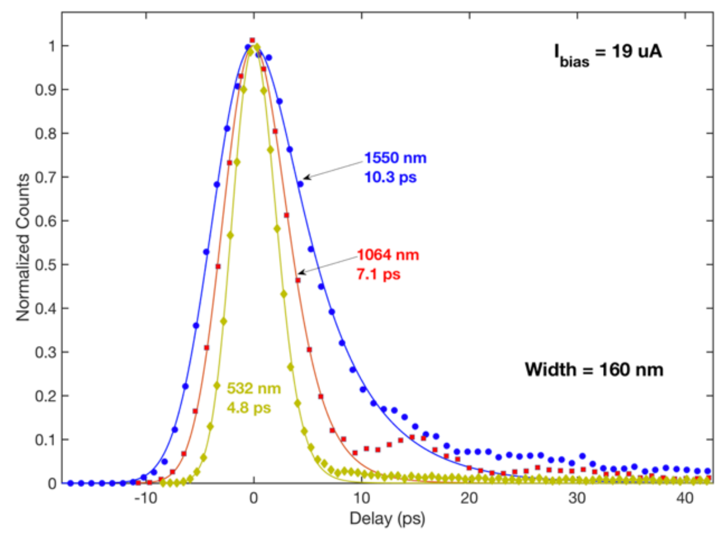
Comparison of Jitter in Different Materials

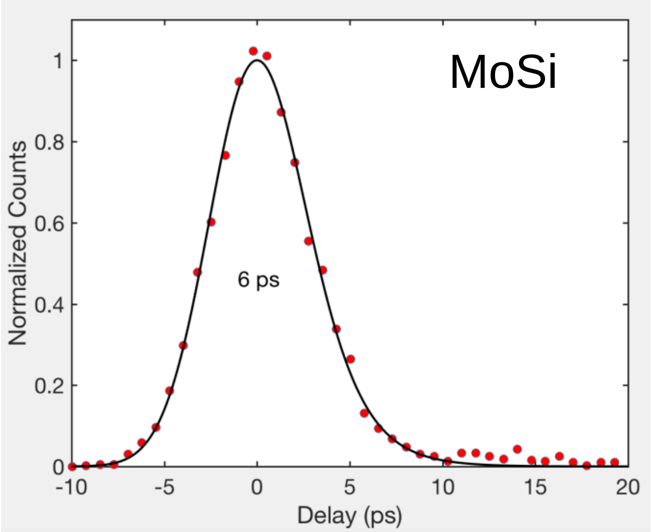
Jet Propulsion Laboratory
California Institute of Technology

NbN



WSi





Thickness (nm)	Width (nm)	L_k (nH)	Best jitter (ps) 532 nm	1550 nm
5	120	200	6.15	10.69
7	100	200	5.97	10.55
9	80	250	7.0	14.42

Applications of ultra-high time resolution

- Ultra-high clock rate quantum and classical communication
  - 1/100 timing distribution < 15 ps: enables 40 GHz clock rates
  - Gbps-scale QKD over short links, or Mbps-scale QKD over lossy channels
  - Higher data rates at longer ranges in free space optical communication

- Photon counting lidar and remote chemical sensing with ~mm resolution per photon
  - Millimeter spatial resolution at km ranges
  - Differential absorption lidar with mm spatial resolution
  - Resonance fluorescence lidar with mm spatial resolution

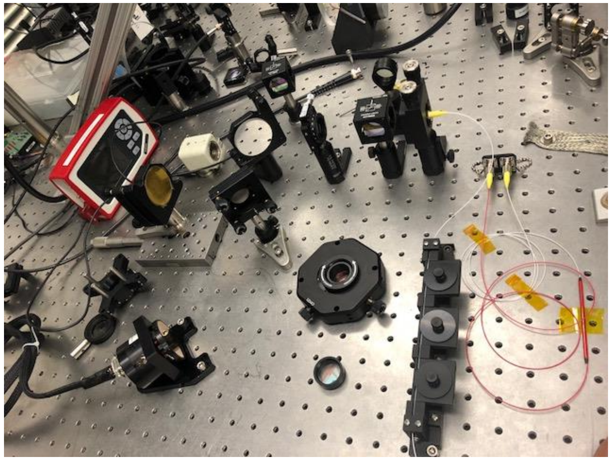
- Biomedical imaging applications
  - Dynamic light scattering for blood flow measurements in neurosurgery
  - Ultrafast FLIM, FCS

- Optical sampling oscilloscope with >100 GHz bandwidth

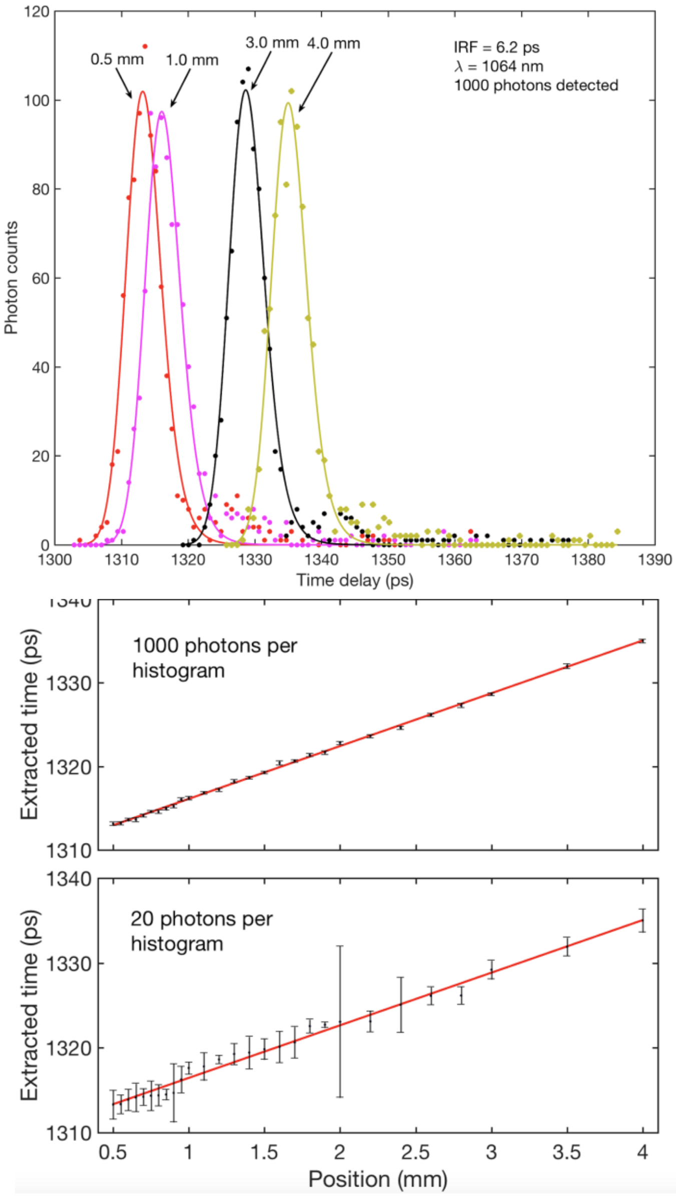
Ultra-high resolution in laser ranging

Jet Propulsion Laboratory
California Institute of Technology

- Improvement in time resolution from ~20 ps to < 3 ps translates into millimeter-scale ranging from each photon
- Dramatic SNR advantage in photon counting lidar systems
- Now performing tabletop laser ranging experiment with record-setting SNSPD and world's fastest timing electronics
- Measured 6 ps instrument response function using time-tagging card

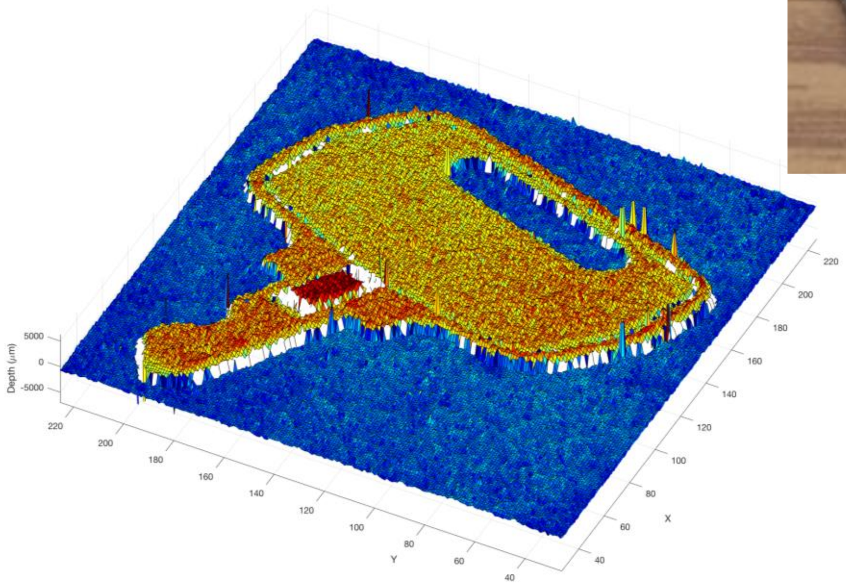


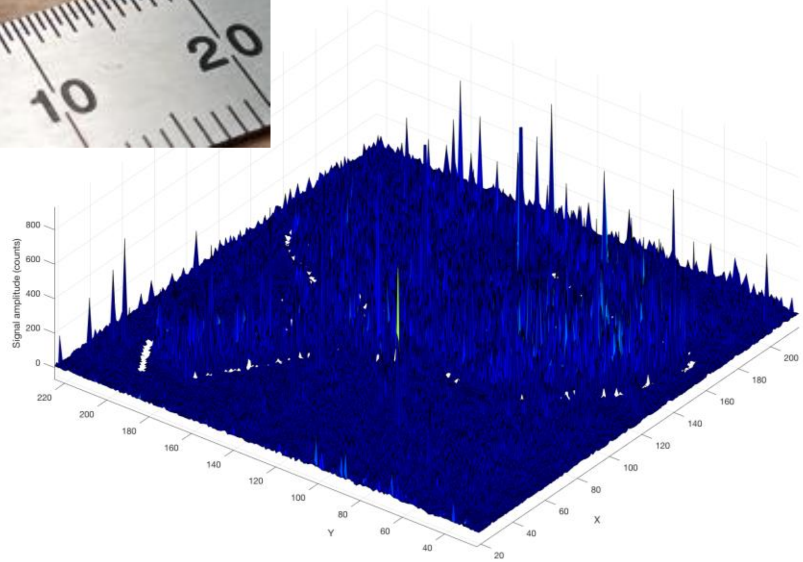
Tabletop laser ranging experiment

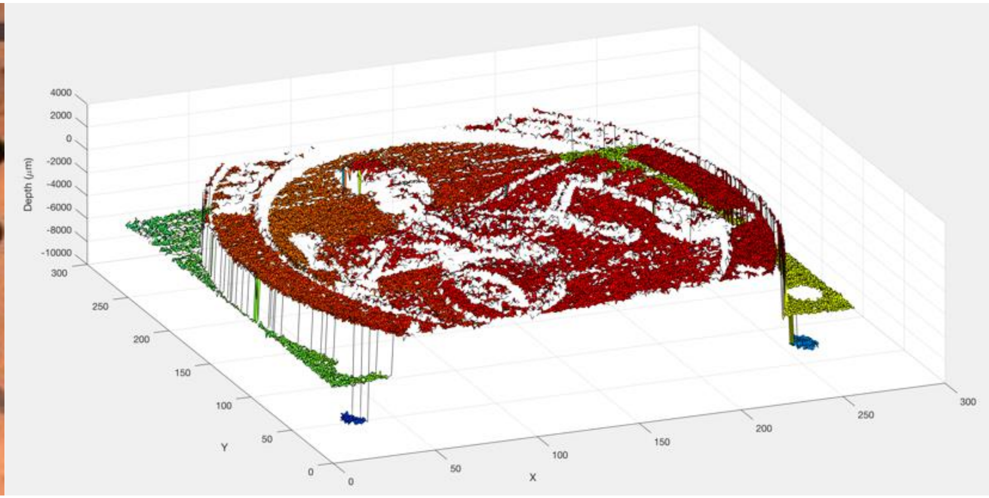


Data from laser ranging experiment showing mm resolution

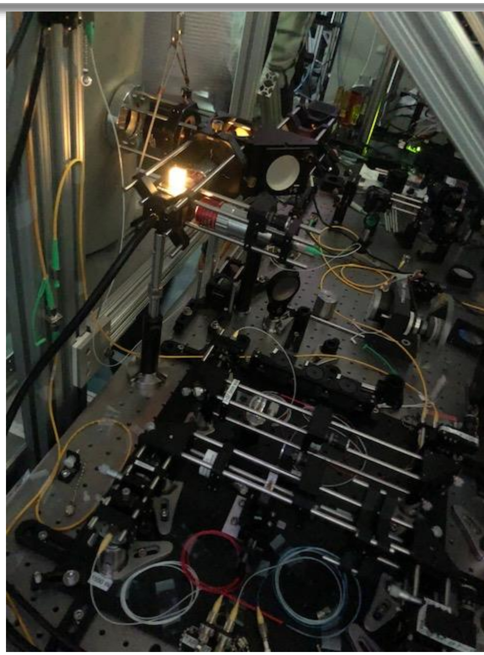
Ultra-high resolution in laser ranging



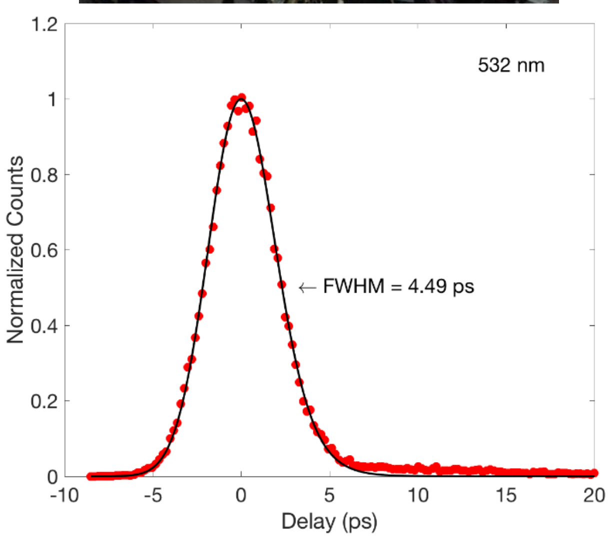




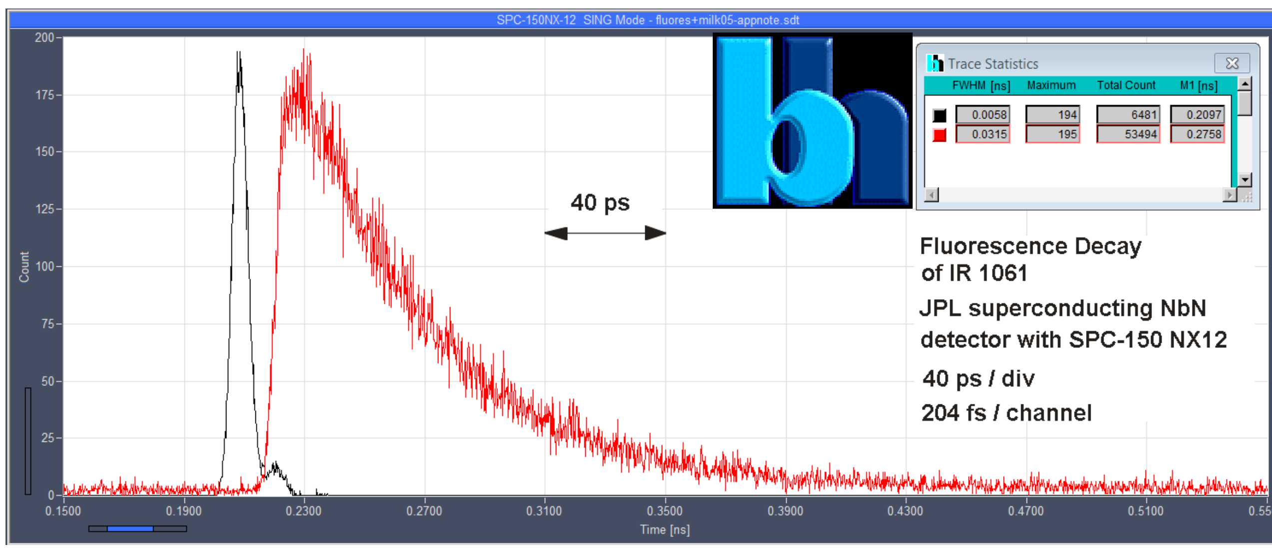
Fluorescence Lifetime Measurements



- Used ultra-low-jitter SNSPDs and modified Becker & Hickl SPC-150-NX to time-tag photon arrivals with < 5ps FWHM
- Measured lifetime of IR-1061 dye in dicholoromethane: 43 ps
- Demonstrates capabilities of ultrafast SNSPDs for remote chemical sensing applications



Time tag data with SNSPD



Fluorescence lifetime measurement of IR-1061 at JPL

Applications of ultra-high time resolution

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- Photon counting lidar and remote chemical sensing with ~mm resolution per photon
  - Millimeter spatial resolution at km ranges
  - Differential absorption lidar with mm spatial resolution
  - Resonance fluorescence lidar with mm spatial resolution

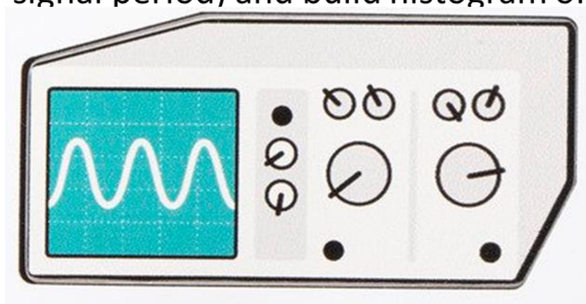
- Ultra high resolution satellite laser ranging

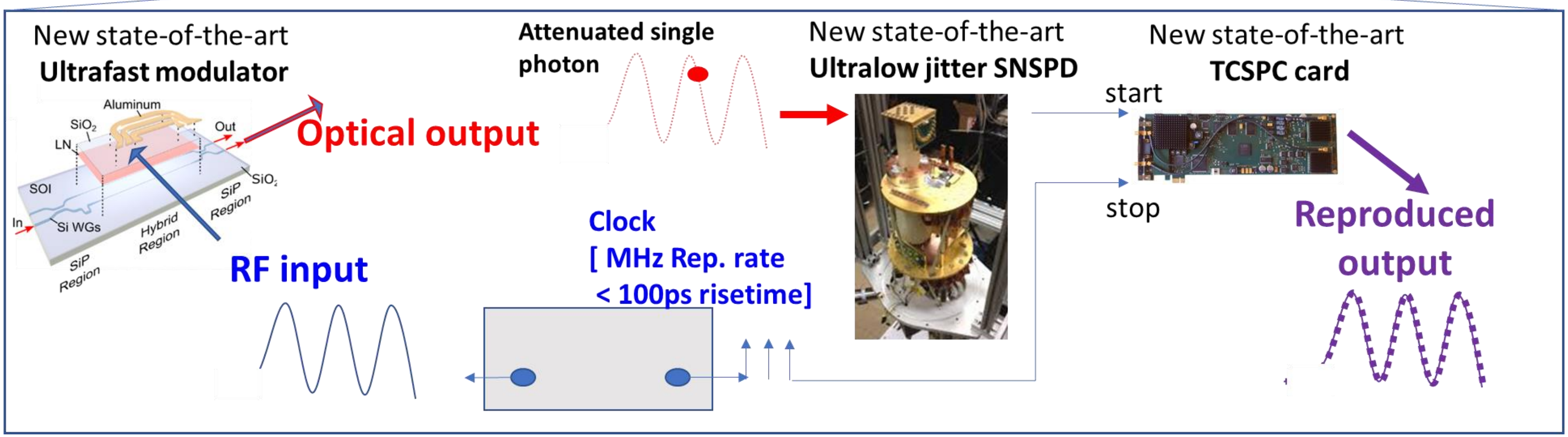
- Optical sampling oscilloscope with >100 GHz bandwidth

- Photon correlation spectroscopy

Optical Sampling Oscilloscope Concept

Concept: Convert fast electrical signals to optical domain (limited by EO modulator bandwidth), then detect single photons (one random photon per signal period) and build histogram of original electrical signal (limited by timing jitter of SNSPDs).

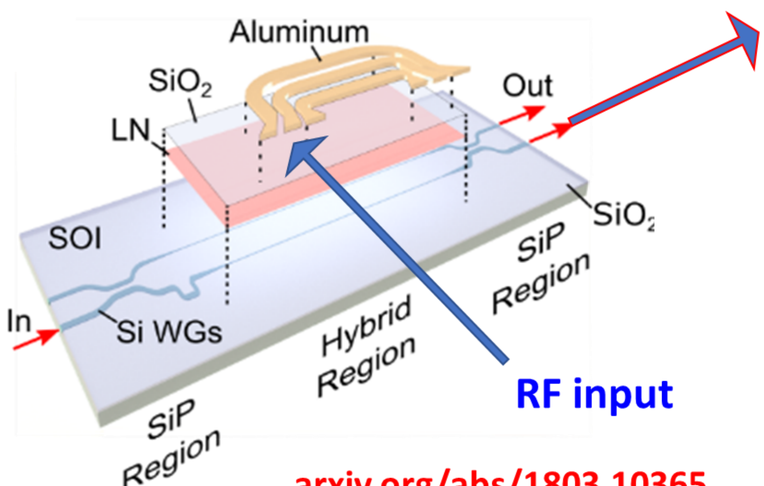




Modulator Technology for OSO

A faithful representation of the fast electrical signal is produced in the optical domain from a hybrid thin film Lithium Niobate silicon photonic modulator.

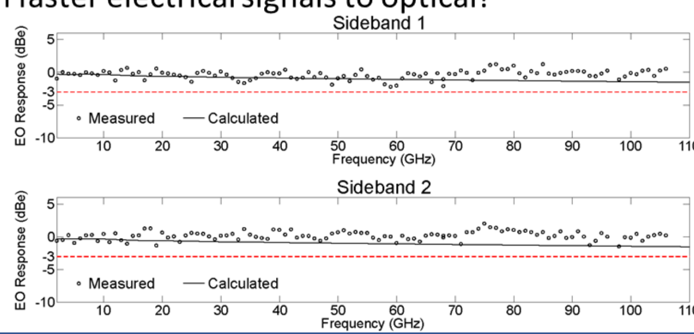
- Measured 1.5 dBe BW ~ 106 GHz
- 3 dBe BW estimated >> 200 GHz (not measured yet due to current RF drive instrument limitation)
- Linear EO response from sideband fall-off indicates that we are far from the point where RF group velocities are mismatched with optical group velocities: this allows a faithful representation of the electrical signal in the optical domain.
- **This is possible due to improved EO conversion from optical modal area (A_eff) being reduced, approx. by 10x – 100x (compared to traditional LiNbO3 waveguides)**



arxiv.org/abs/1803.10365

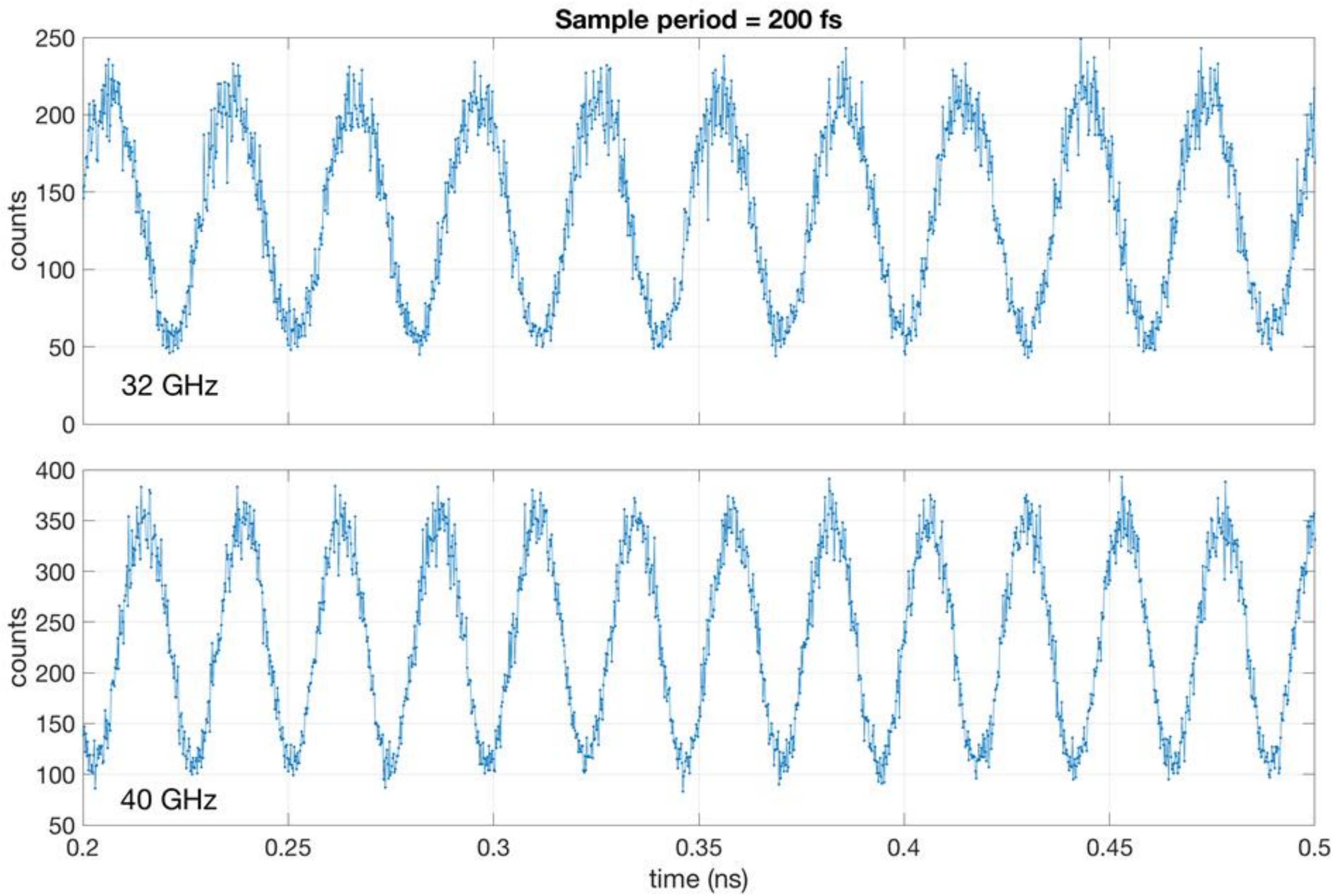
Optical output

Measured data: Sideband amplitudes on high-DR, high-res OSA. RF velocity is NOT mismatched with Optical, we can convert even faster electrical signals to optical!



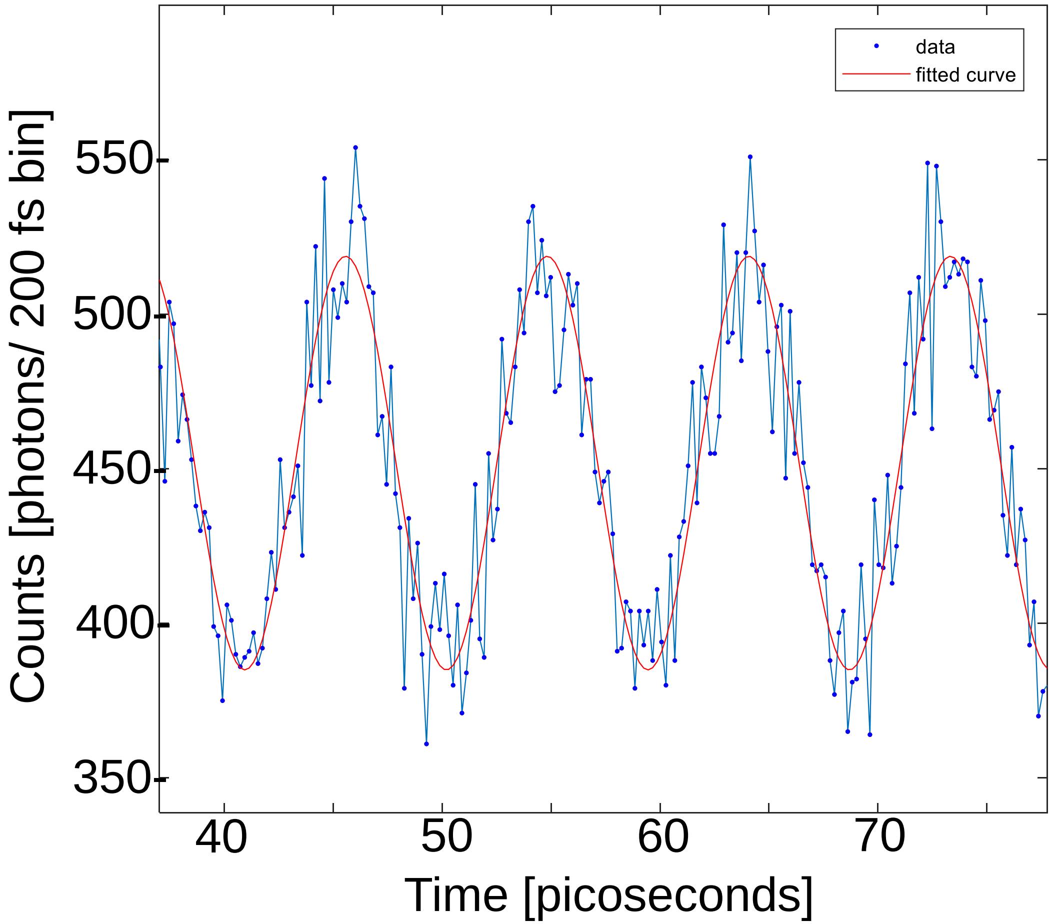
Preliminary 40 GHz Results

- Modulator driven with Anritsu 40 GHz source
- Collection time 10 s
- Photon acquisition rate: 1 Mcps
- Sample period can be optimized to minimize noise
- Optical power range: approx. -50dBm (no optical amplifiers required for operation)

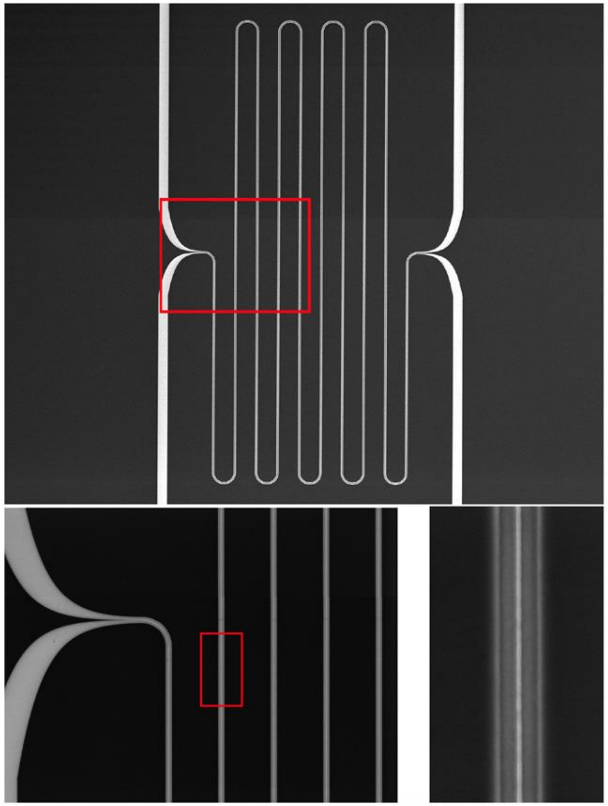


Preliminary 102 GHz Results

- Modulator driven with Anritsu 40 GHz source @ 17 GHz, multiplied x6 by AMC10, and amplified by GaAs-GaN chain
- 108mW (6.5V) RF power delivered to chip probes
- Collection time 120 s
- Photon acquisition rate: 0.5 Mcps
- Sample period can be optimized to minimize noise



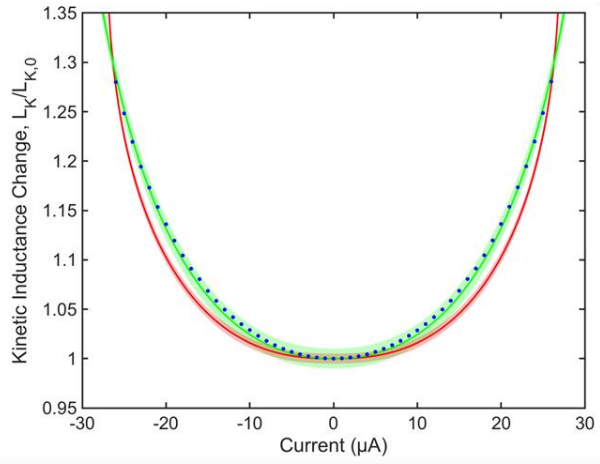
Resonator Measurements

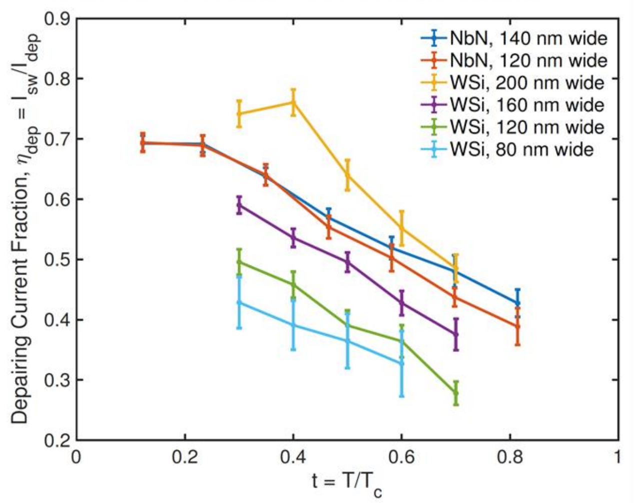


Depairing current measurements

- Measurements of the resonance frequency as a function of bias current
- Fitting to model allows the determination of the depairing current
- Crucial new technique for SNSPD material characterization
  - Provides **direct** information about the quality of superconducting nanowires
  - Key parameter for modelling

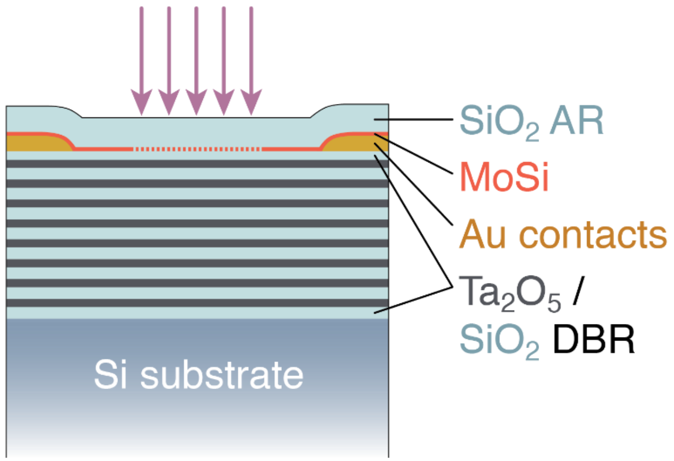
High fraction of depairing current leads to improved long-wavelength cut-off

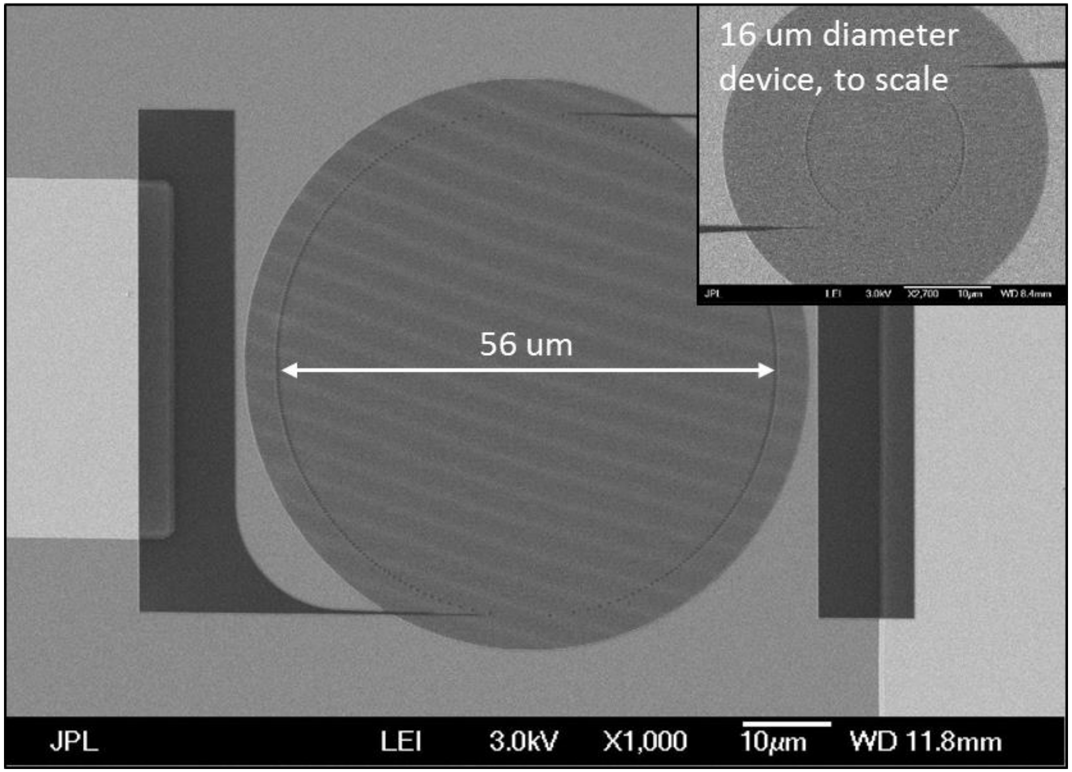




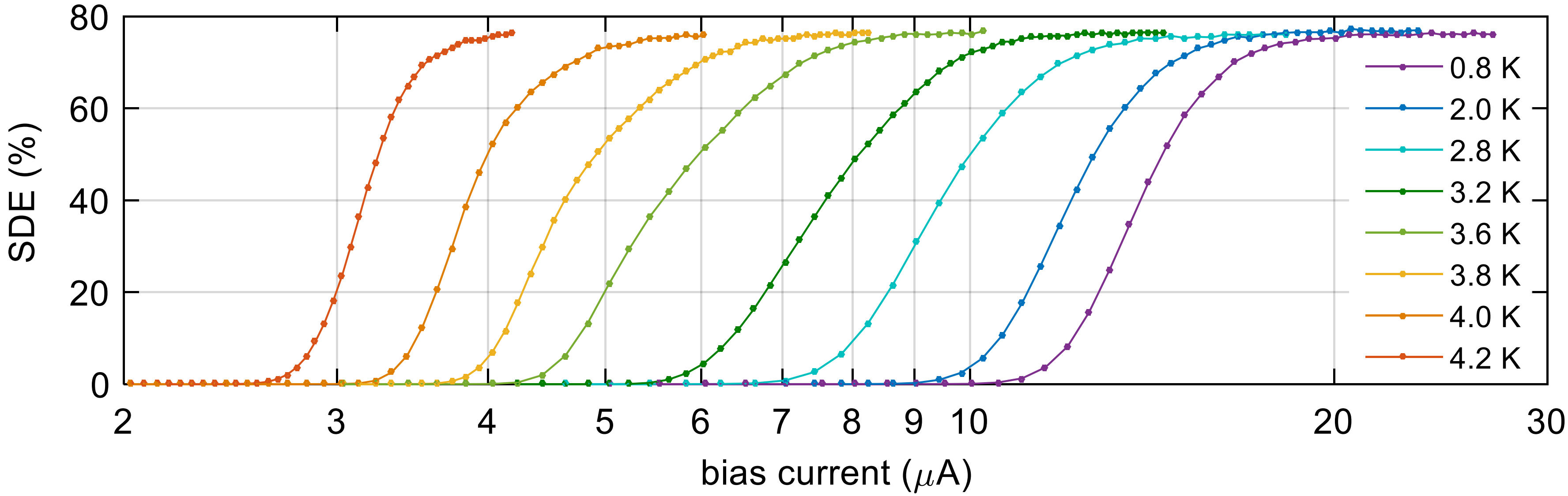
Ultraviolet SNSPDs for Quantum Computing

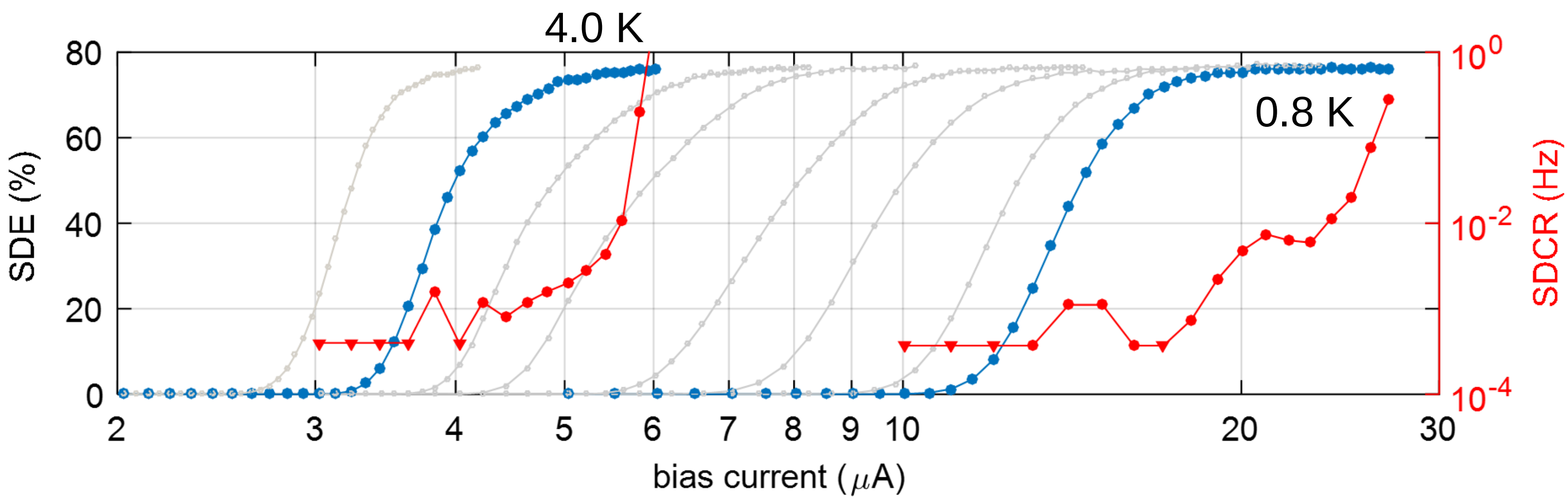
- Fiber-coupled MoSi UV SNSPDs for applications in ion trap quantum computing
- 80% Efficiency at 370 and 315 nm, single photon sensitivity at 245 nm
- DBR mirrors to enhance absorption
- 4.2 K operating temperature
- mHz dark count rates when coupled to optics, < 7e-5 cps intrinsic dark count rates





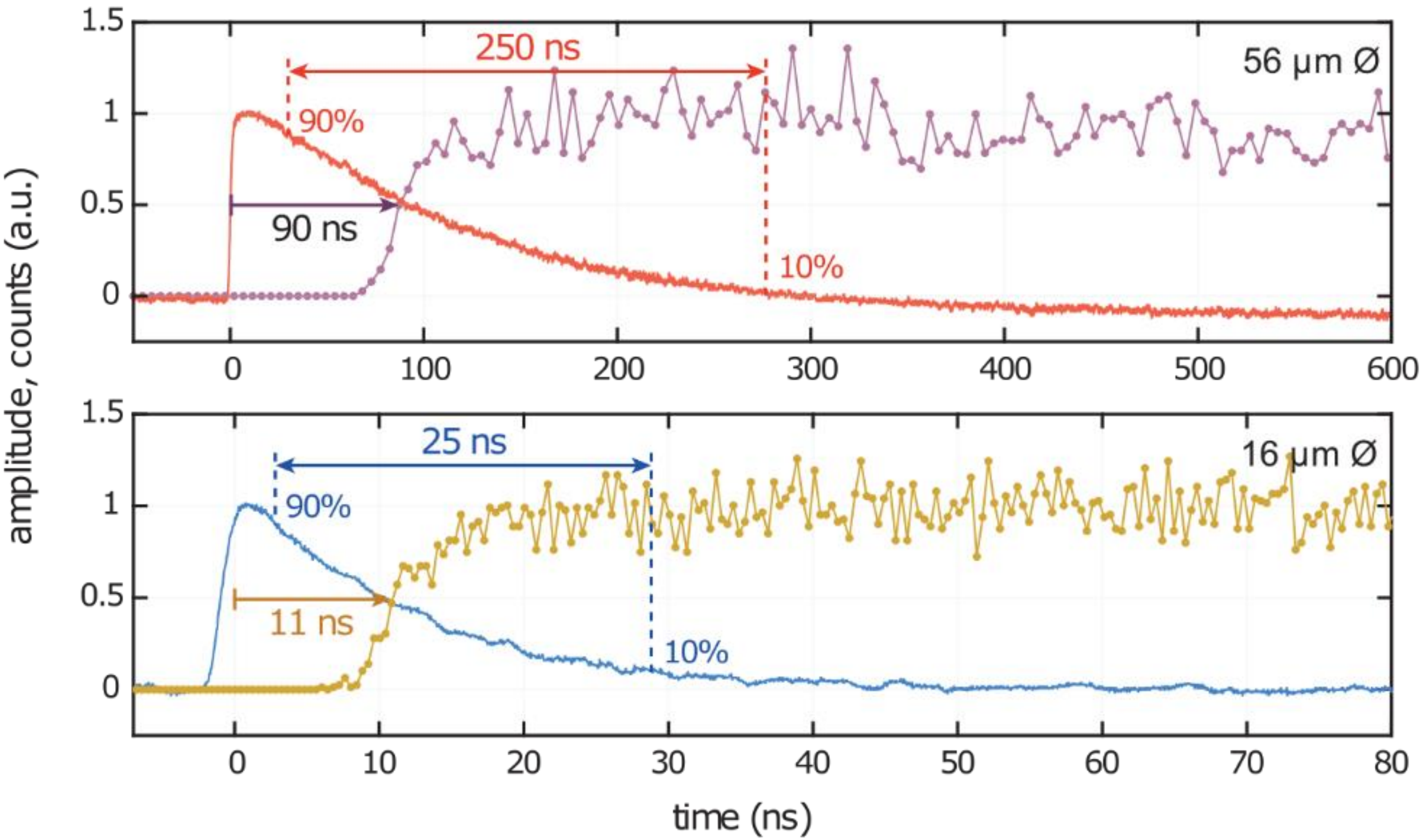
Efficiency and Dark Counts at 370nm



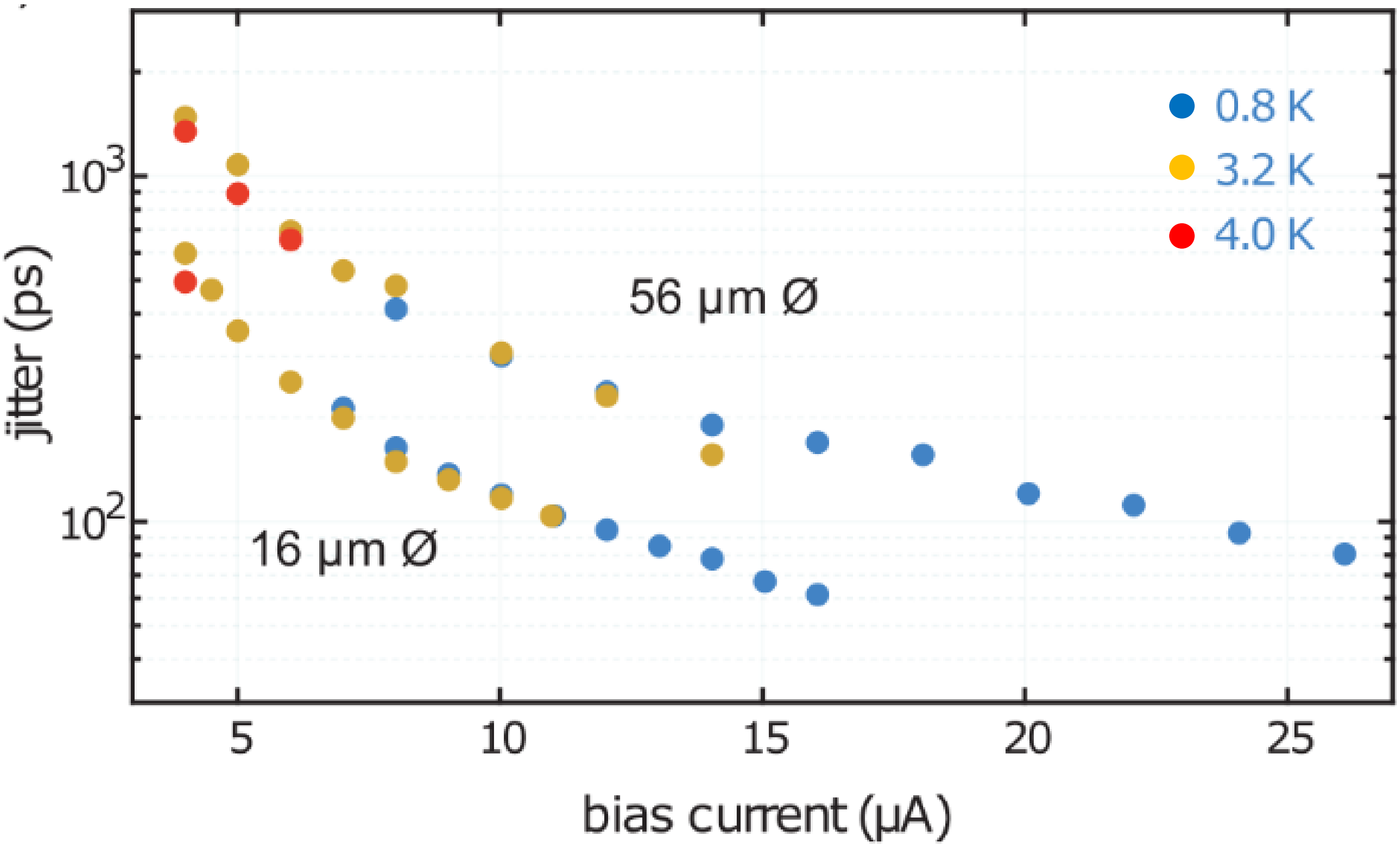


Dead Time of MoSi UV SNSPDs

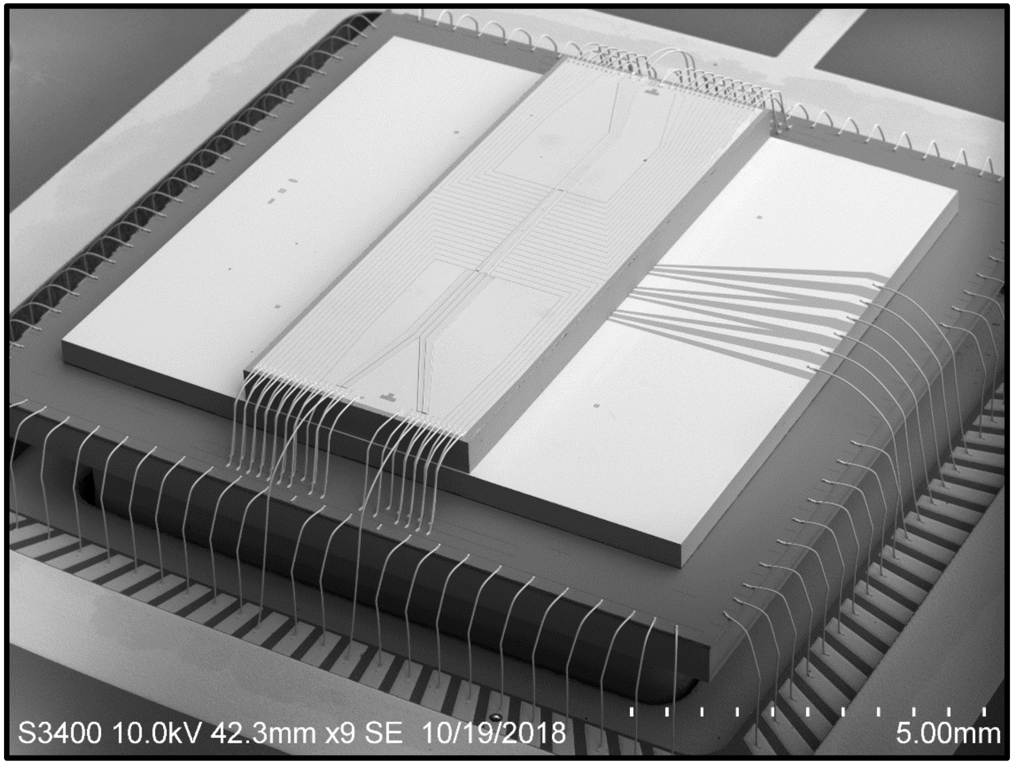
Jet Propulsion Laboratory
California Institute of Technology



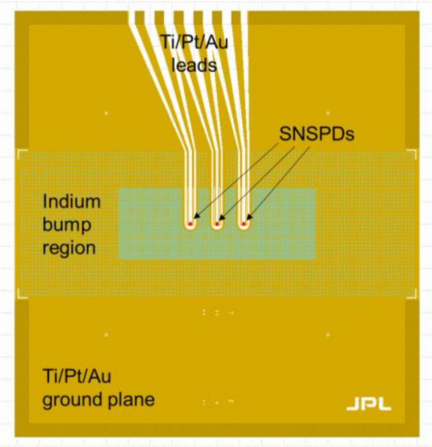
Jitter of MoSi UV SNSPDs

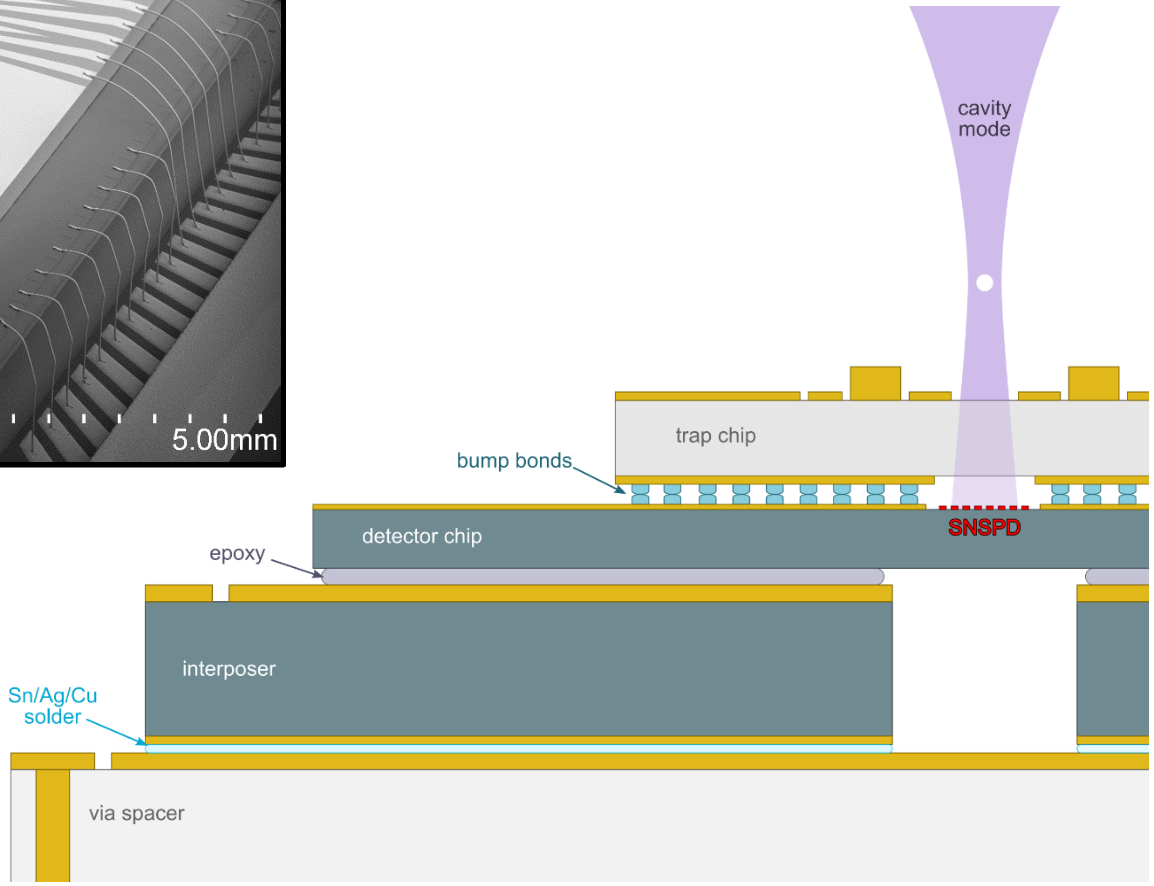


Integration with Ion Trap Chips



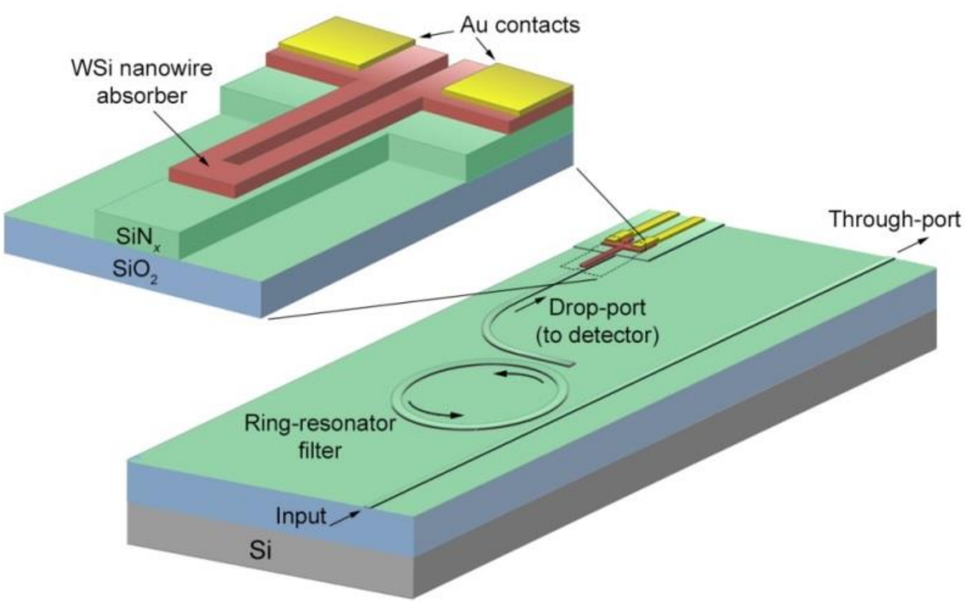
- Hybrid integration between ion trap chips and free-space UV SNSPDS
- Collaborative effort between JPL, NIST, Sandia, and Duke University

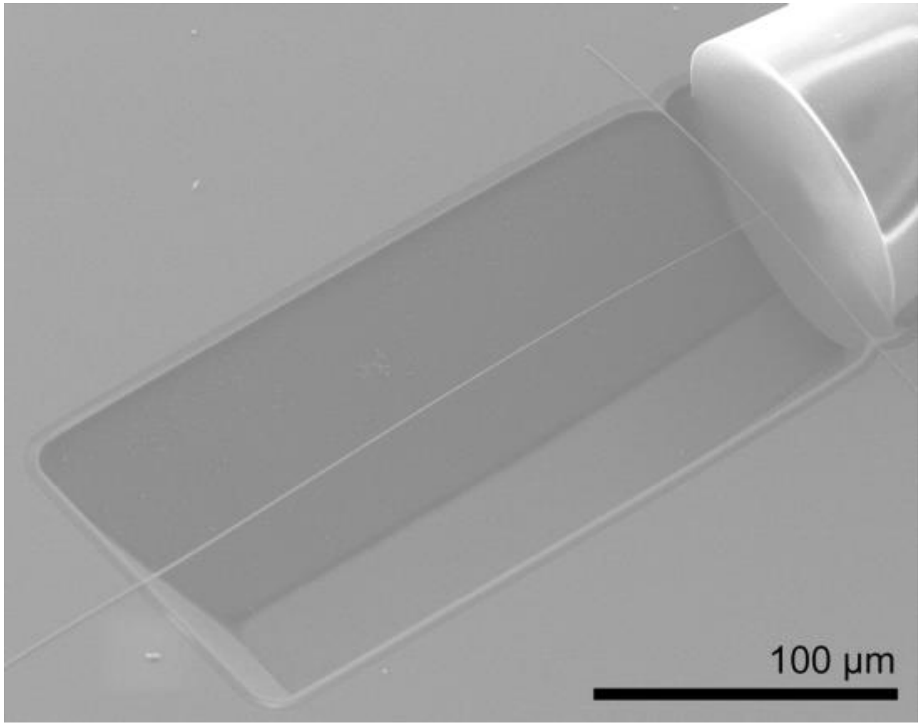




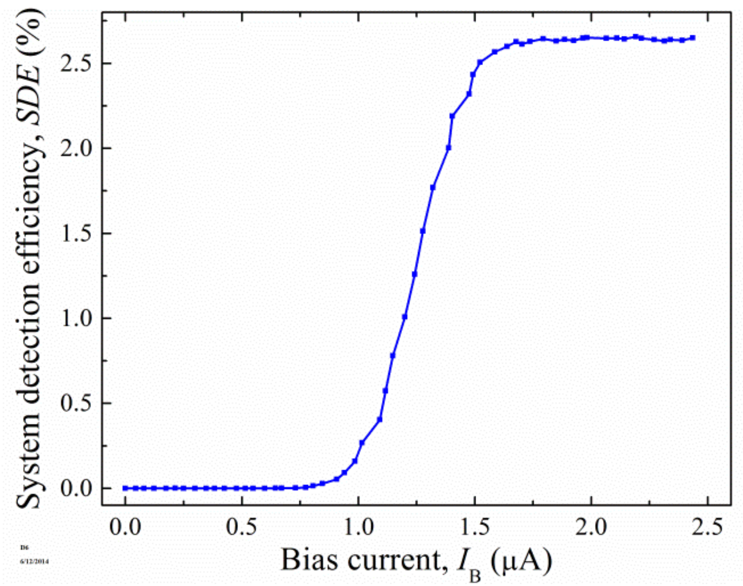
On-Chip Integrated SNSPDs

- WSi SNSPDs coupled to SiN waveguide photonics platform
- Integration with low-loss broadband optical couplers (Collaboration w/ Painter Group, Caltech)
- Integration with on-chip ring resonators or echelle grating to form channelizing spectrometer or DWDM receiver for QKD
- Can be integrated with on-chip heralded single photon sources, photonic processors, or photonic trapped ion systems
- Can realize a robust, on-chip cryogenic spectrometer, particularly in the mid-IR

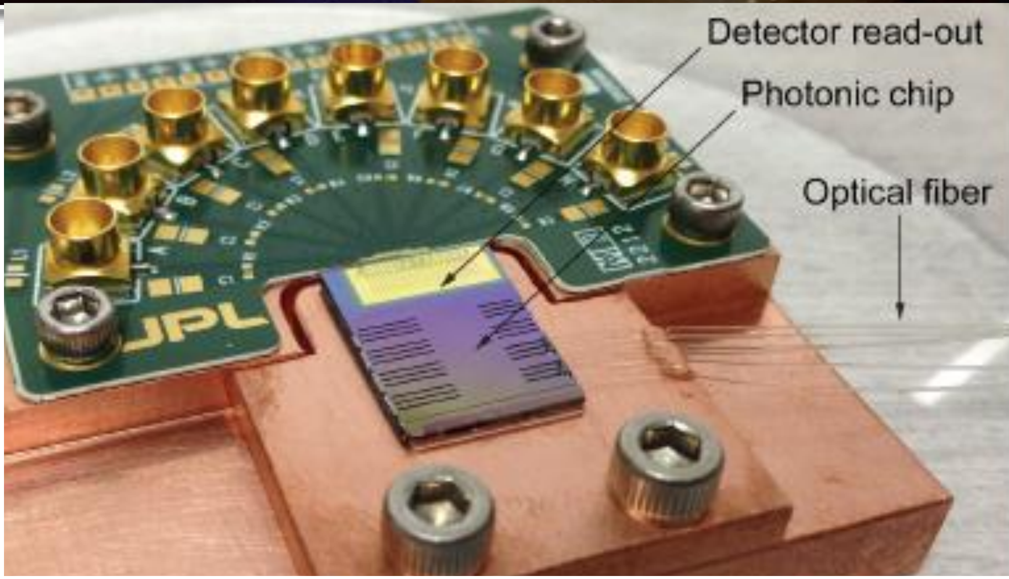




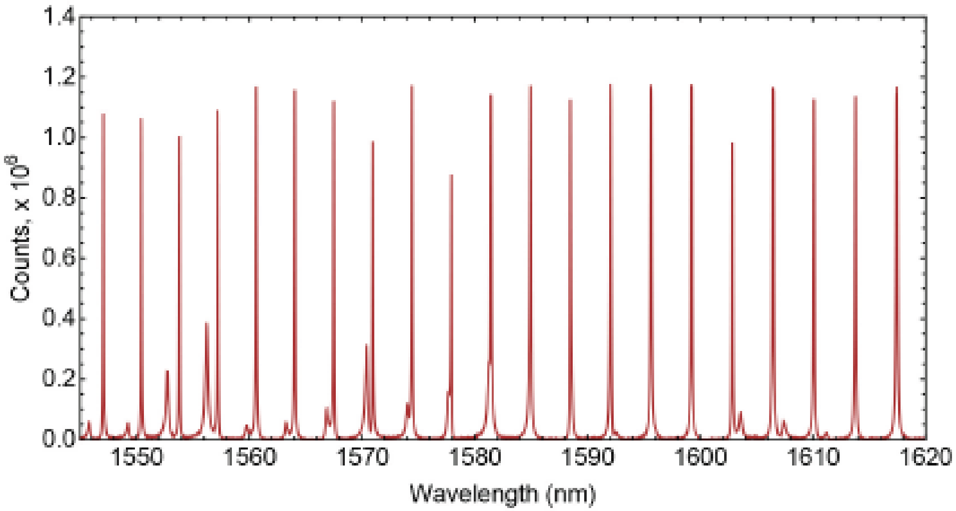
On-Chip Integrated SNSPDs

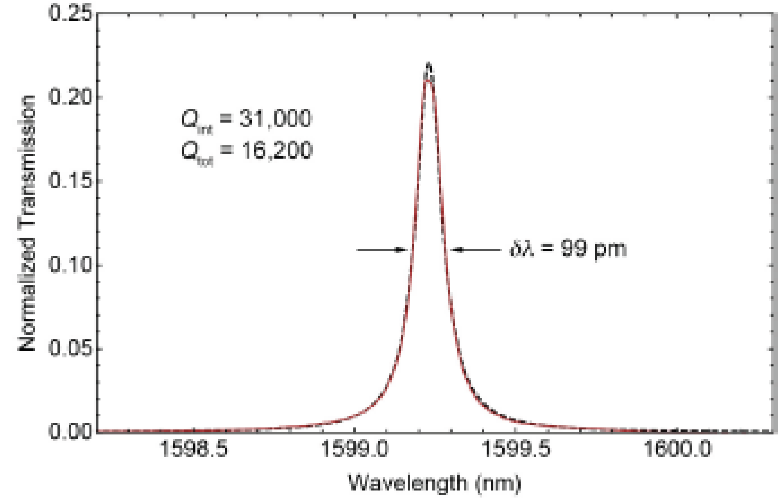


WSi SNSPD in waveguide with bias plateau



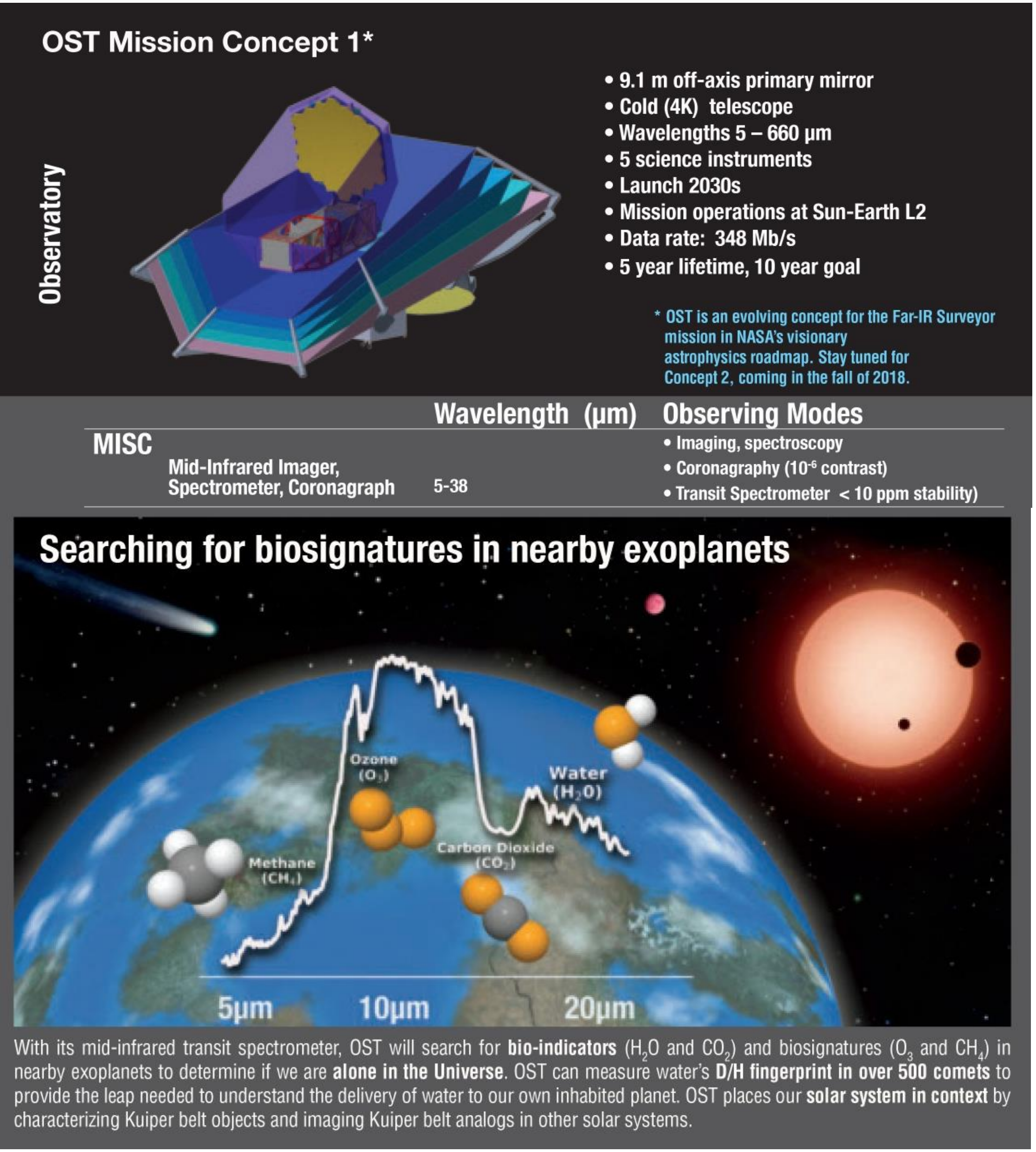
Cryogenic self-aligned fiber packaging





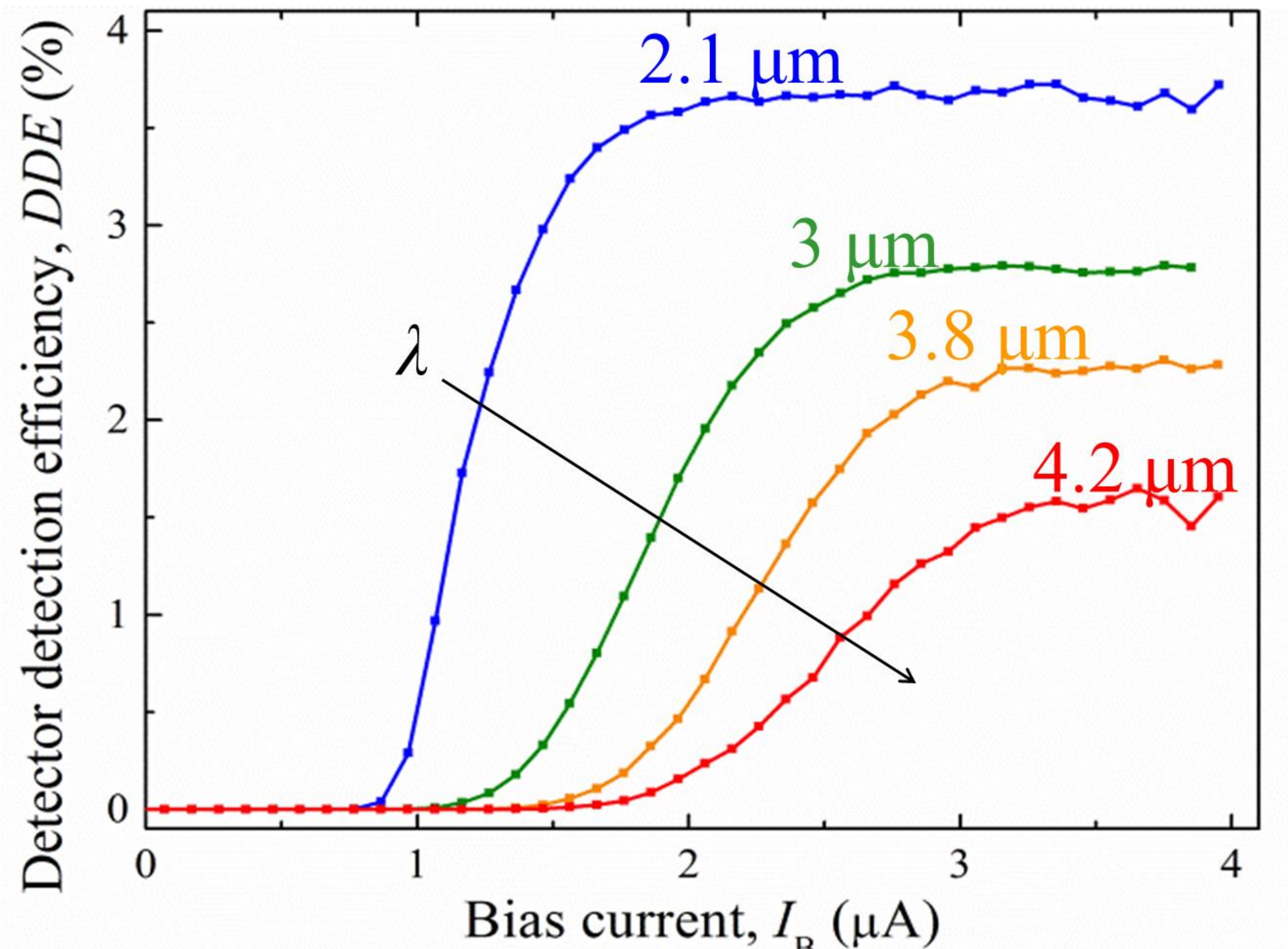
Wavelength selectivity of count rate using SNSPD integrated with photonic ring resonator

SNSPDs for Exoplanet Transit Spectroscopy



- Origins Space Telescope is a proposed mission concept for a future space-based infrared observatory beyond JWST
- OST Science Team is interested in SNSPDs for MISC instrument to perform exoplanet transit spectroscopy
- Need ultra-stable photometery to resolve 5-10 ppm spectral features from 6-20 µm
- Need to make efficient SNSPDs at mid-IR wavelengths, scale to kilopixel arrays
- Competing technology are BIBs and MCT detectors

SNSPD response in the mid-infrared

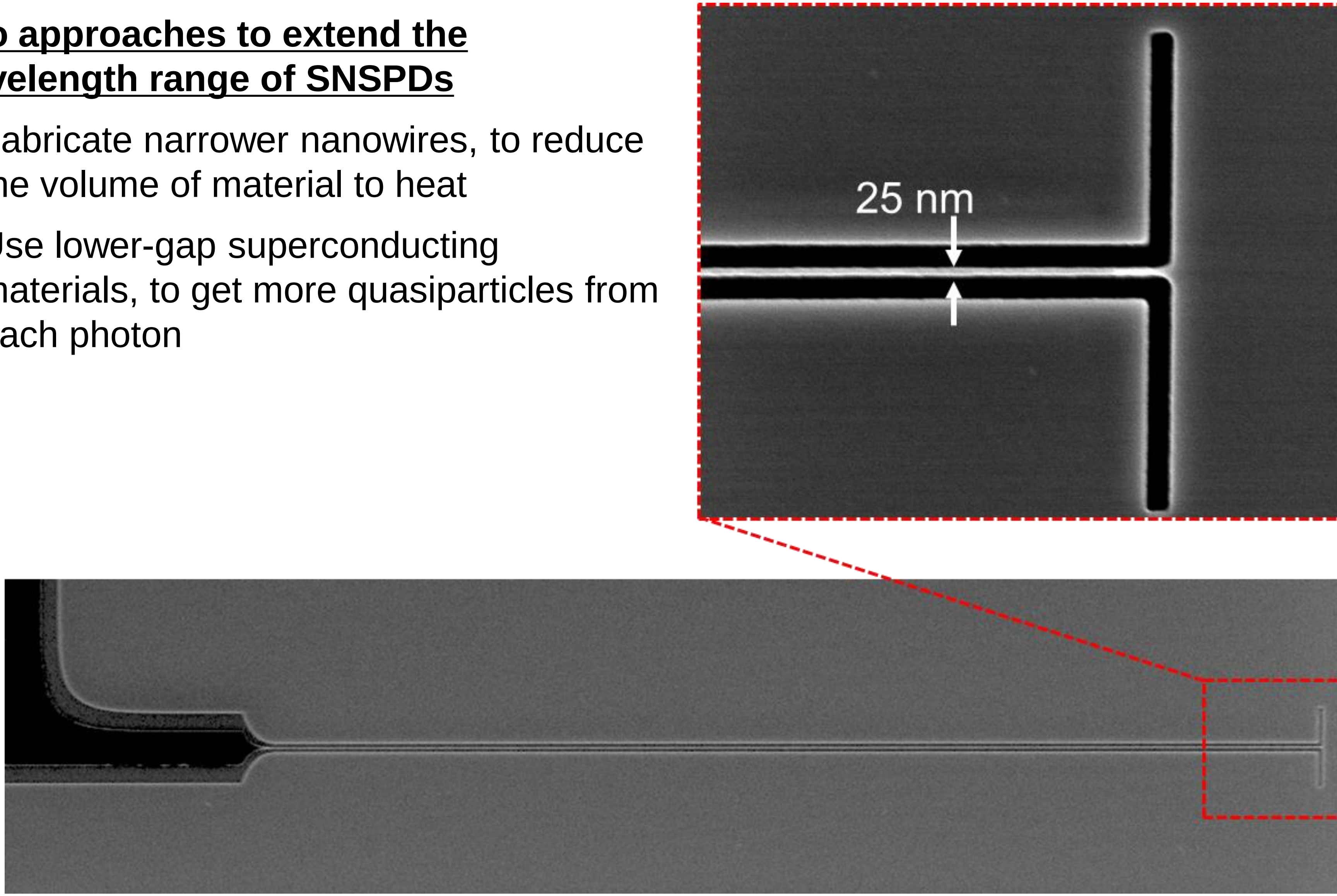


Stevens and Marsili, *Proc CLEO* (2013)

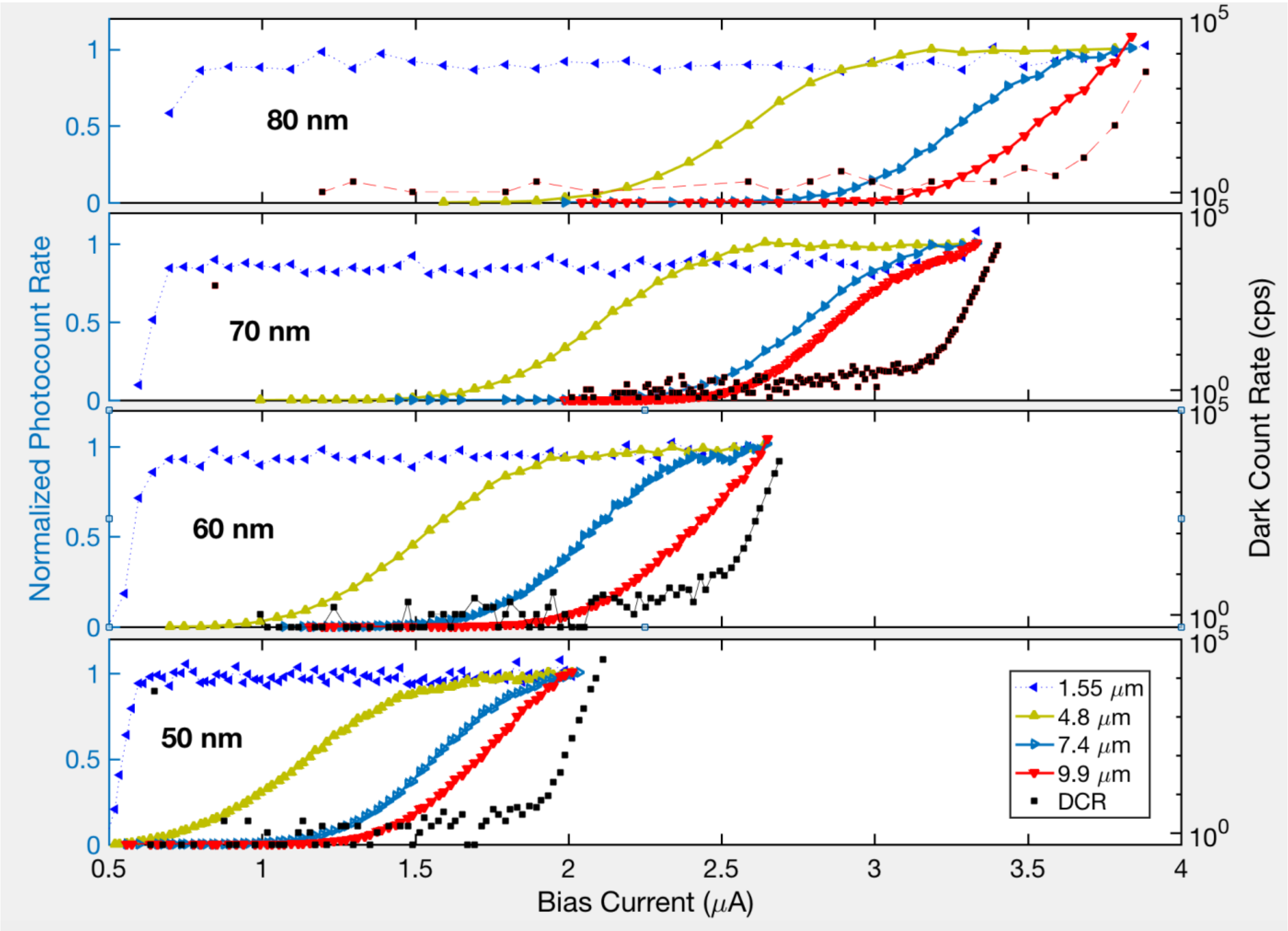
SNSPD response in the mid-infrared

<u>Two approaches to extend the wavelength range of SNSPDs</u>

- Fabricate narrower nanowires, to reduce the volume of material to heat
- Use lower-gap superconducting materials, to get more quasiparticles from each photon



Preliminary Results with Low-Gap WSi



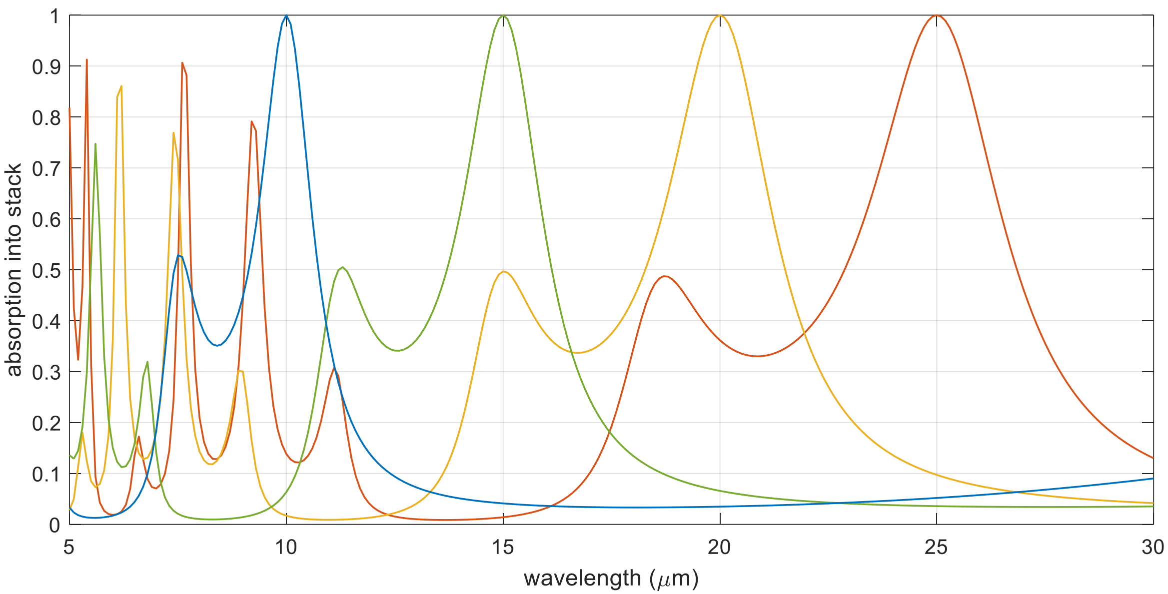
- Reducing Tc for better long wavelength sensitivity with wider nanowires
- Regular WSi, 3.6 K
- Tc = 3.1 K
- Next devices: 2.8 K

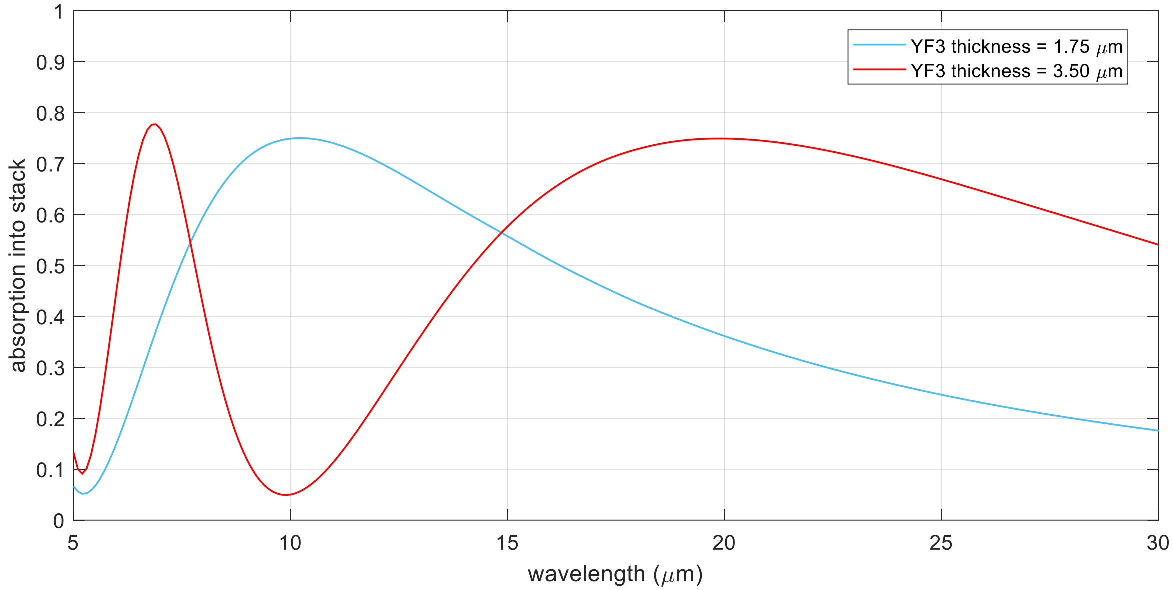
Collaboration with NIST: Varun Verma, Heli Vora, Adriana Lita, Sae Woo Nam

Mid-IR Optical Stack Designs

Jet Propulsion Laboratory
California Institute of Technology

- Need to identify materials for MIR optical stacks
- Low index: YF3
- High index: ZnSe, ZnS, (aSi?)
- Index of refraction of WSi is very high at MIR wavelengths – not well-matched to air
- Strong polarization dependence
- Explore multi-layer SNSPDs to increase absorption, decrease polarization dependence





Technology Development Priorities

- Devices which combine <10 ps jitter, >80% efficiency, and >1 Gcps count rates **simultaneously**
  - Differential readout of NbN SNSPDs in a cavity
  - Time-to-digital converter development to support larger arrays
- Multiplexing architectures which enable scaling to kilopixel arrays and beyond
  - Thermal row-column, thermally coupled imager, frequency multiplexing, SFQ readouts
- High detector performance in the mid-infrared
  - Narrow nanowires with low-gap material for space telescope applications
  - Integrated cryogenic filters for terrestrial applications
- Millimeter-diameter active areas and >10 Gcps maximum count rates
  - Necessary to support a future optical Deep Space Network
- Space qualification of SNSPDs for flight applications
  - Low-power flight cryocooler development
  - Radiation testing of SNSPDs

Summary

- SNSPDs are a powerful platform for time correlated single photon counting from the UV to the mid-infrared
- Rapid advancement has been made over the state of the art with semiconductor detectors
- SNSPDs have room for orders of magnitude improvement in many parameters
- SNSPDs are enabling ambitious new demonstrations of laser communication from deep space